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Design Procedure for HFM Quadrupole Model End Parts

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- ***Abstract***—*This technical note provides detailed guidelines on the design of cosine-theta type magnet end parts from a given cross-section. The starting point for any end part design is the given 2-D magnet cross-section. The cross-section used here is the one detailed in Fermilab Technical Note TD-02-012 [1] and is also shown in Fermilab drawing number 5520-MC-411284 [2]. The drawings of the bare and insulated cable for this cross-section are numbered 5520-MC-411285 and 5520-MC-411286 respectively. Fermilab drawings 5520-MC-411370 [[1]] and 5520-MC-411371 show the coil assembly for the inner and outer layers of the given cross-section. Here, we present detailed step-by-step procedures for the design of magnet end parts. In a separate technical note (provide reference), we will provide detailed guidelines for making coil solid model from the given design data.*

1. Introduction

Obtain the Roxie program output of the coil to be designed. This will provide the coil's cross-section. The cross-section will define the groups X-Y plane geometry requirements. Lets begin by naming the components, which make up one-quarter section of a Quadrupole coil.

First is the Inner Layer, this layer is composed of the Lead End parts, the Return End parts and the center transition section. Each Lead End part is made up of a right side

[1] V.V. Kashikin and A.V. Zlobin, "Nb3Sn Quadrupole Coil in MQXB Collar," Fermilab Technical Note TD-02-012, March 2002.
2

and a left side. The Return End parts are symmetrical, both right and left sides are the same. The Center transition section allows the cable to have a connection path between the inner layer and the outer layer of the coil.

A little background information on how the coil is wound will aid us in the orientation of the coil. The cable, for our example, is 50 meters long. It has a keystone cross section, with the thicker edge considered to be the top. Half the length of the cable is wound on a spool and the other half is wound on another spool. The coil-winding machine rotates on a turntable. There is a center mandrel to which the inner layer end parts and center transition part are attached.

One of the cable spools is mounted, above the winding mandrel, on a rotating pivot. The other coil spool is mounted to the cable tension machine. The center of the cable length (25meters) is clamped to the inner layer center transition piece. In our example, the center transition piece will have the cable start on our right hand side and be on the near side of the mandrels centerline. The Lead End is to our right and the Return End is to our left. The cable winding direction is in the clockwise direction.

The Lead End, end parts are made-up of having a left side and a right side. Our example considers the centerline of the mandrel as the dividing plane of the end parts, with the Lead End to our right hand side. That which is considered to be the right side of a Lead End part is on the far side of the mandrels centerline. That which is considered to be the left side of a Lead End part is on the near side of the mandrels centerline. See Figure 1.

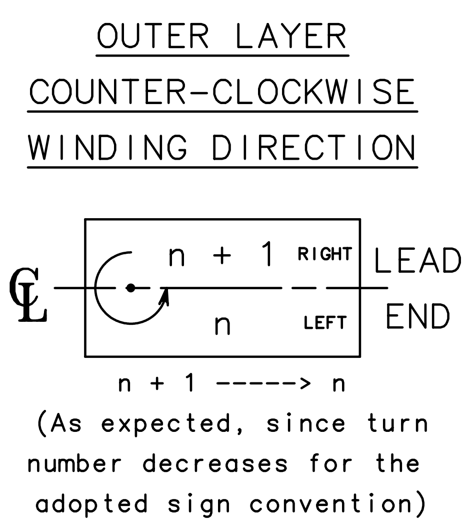

Figure 1: Mandrel winding direction.

Now lets begin the End Parts design.

Having the Roxie data sheet and cross section drawing file we can determine the conductor group name, the conductor number and the number of conductors in each group. To be consistence the following conductor numbering rules will be maintained for the Inner Layer:

1) For all conductor numbers, starting angle and edge angle are computed for the side closer to the pole.
2) The center pole piece, side with out transition is equal to the side with the transition plus one.
3) The turn number, of the coil, changes at the centerline of the Lead End.

For the Outer Layer:

1) For all conductor numbers, starting angle and edge angle are computed for side closer to the pole.
2) The center pole piece, side with out transition is equal to the side with the transition minus one.
3) Turn number changes at the centerline of the Lead End.

We are interested in the areas between the conductor groups. This is where the End Parts will go. Looking at our cross section drawing we can see that each conductor group is composed of a certain number of conductors. In our example there are 3 conductor blocks. The outer layer is assigned the name Block 1` and has 15 conductors, numbered 1 through 15. Block 2 and 3 are assigned to the inner layer. Block 2 has 12 conductors, numbered 16 through 27. Block 3 has 2 conductors in it and numbered 28 and 29. Figure 2: shows the cross-section of the quadrupole model.

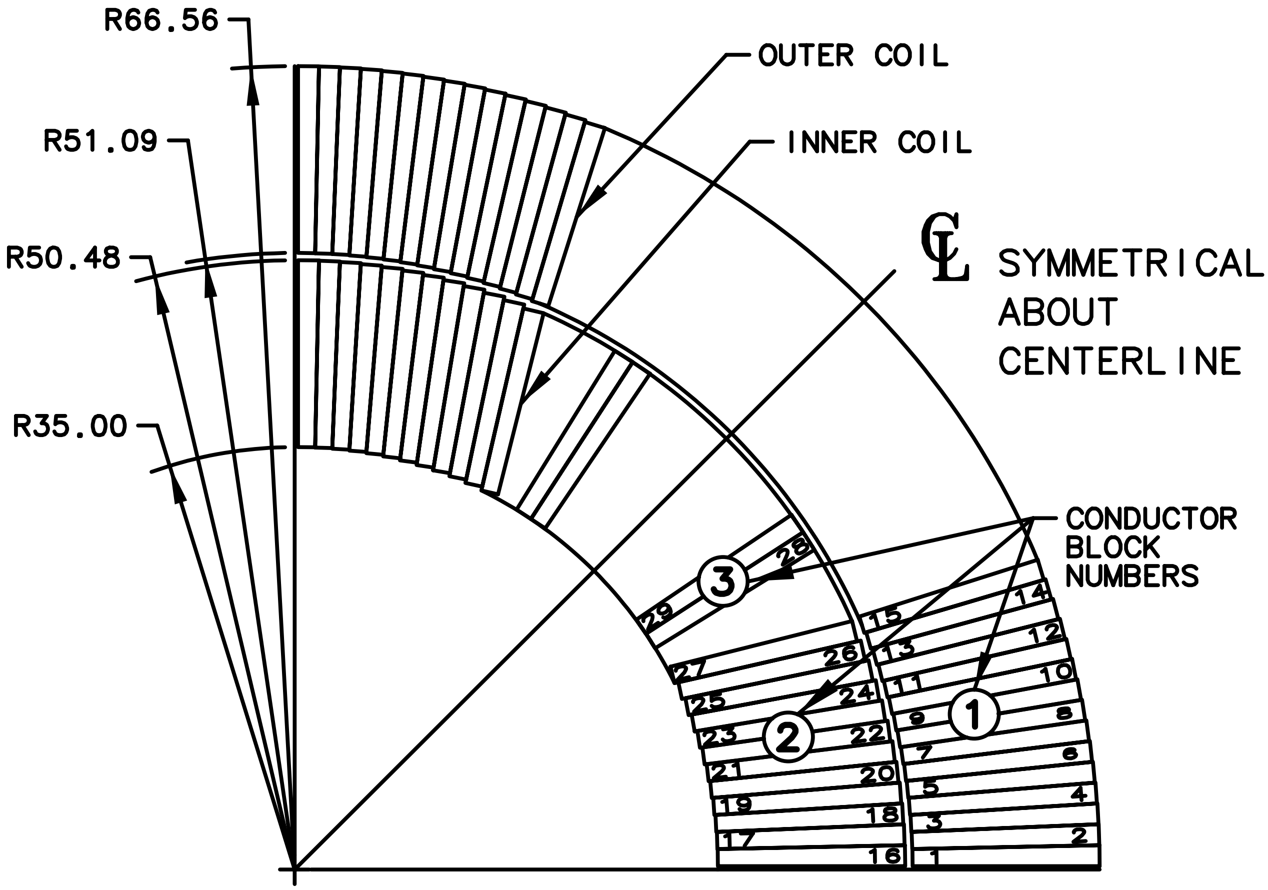

Figure 2: Cross-section of the Quadrupole model.

To determine the minimum number of End Parts required, see Appendix #1. Knowing which conductors boarder the End Parts we are now able to obtain the Insulated cable, corner point, X-Y coordinate locations from the Roxie data. Focusing our attention on the Inner layer Lead End we will establish the naming convention for our end parts.

Figure 3 & Figure 4 represent the cross-section of the lead and return ends of the quadrupole model. It also shows the convention used for naming the conductor groups in the end. The first alphabet of the name represents whether it is the inner layer (I) or the outer layer (O). The second alphabet represents if it the lead end (L) or the return end (R). The conductor groups are then numbered sequentially starting from the first wound conductor group to the last wound conductor group. Note that since the lead end parts are not symmetrical, there are two different files for each conductor group represented by the third alphabet for the lead end side input files: (L) for the left hand side and (R) for the right hand side.

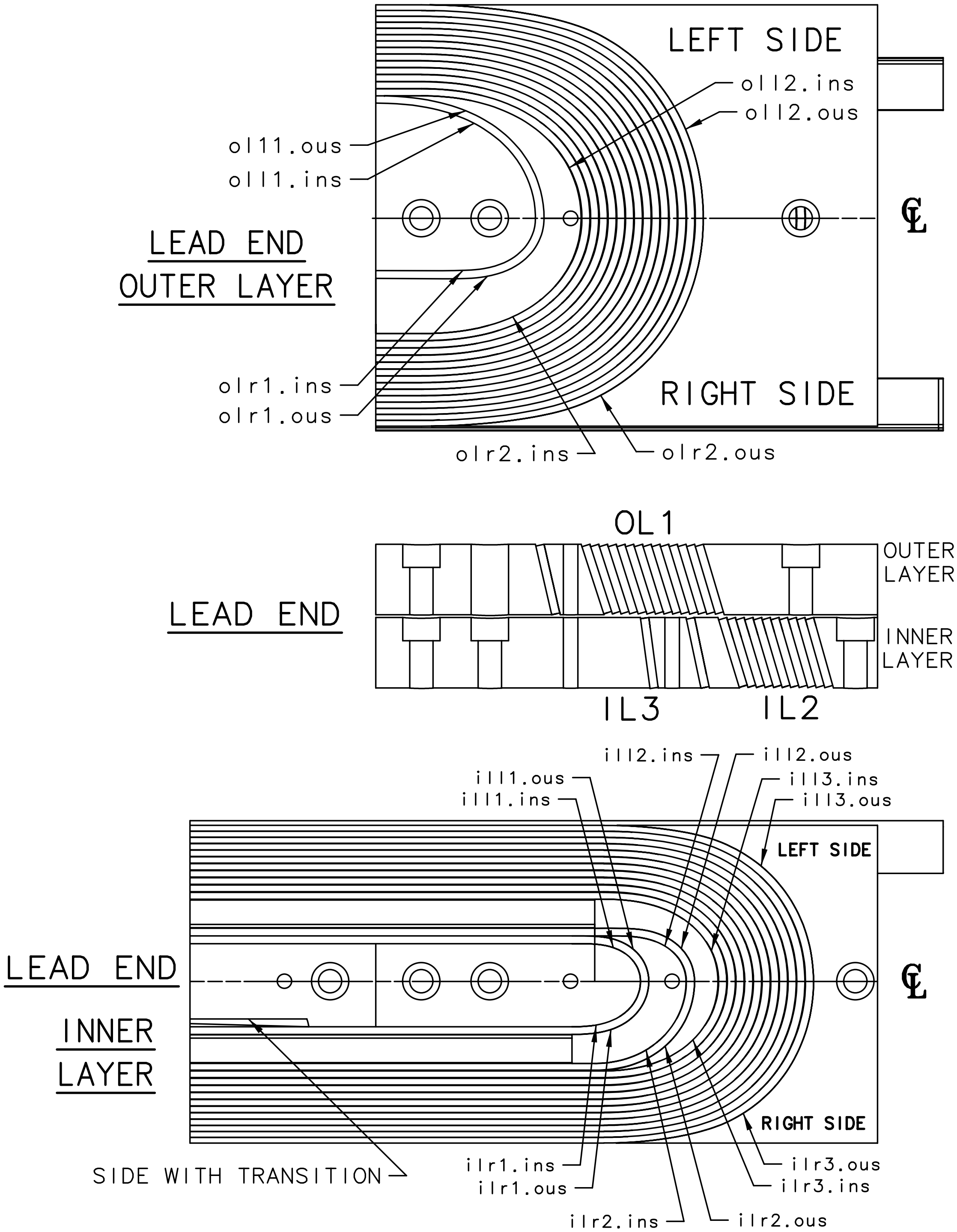

Figure 3: LEAD END: plan views and cross-section

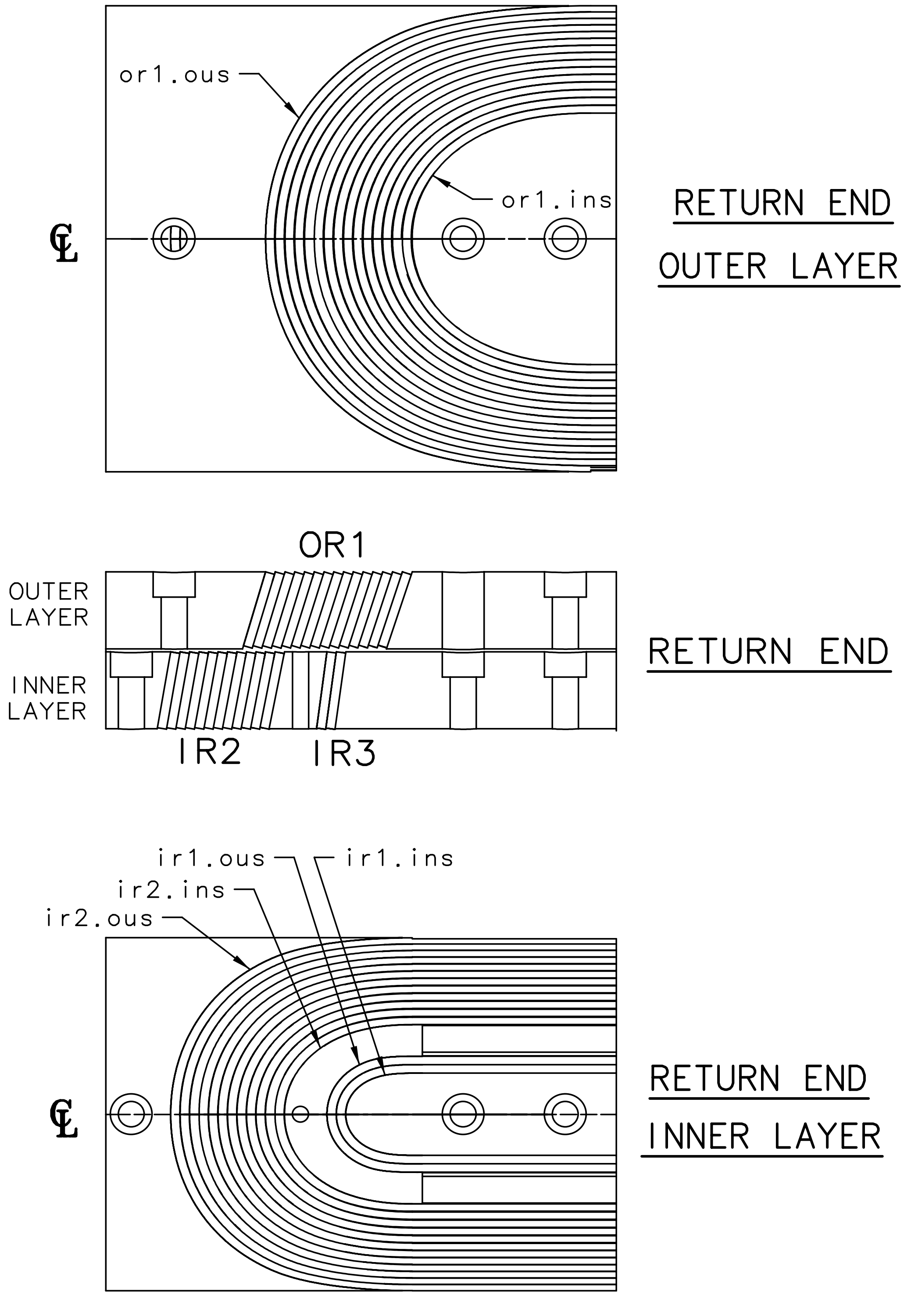

Figure 4: RETURN END: plan views, cross-section.

We can observe from the cross-section drawing (see figure 2) and knowing what conductor number is used in the inner layer transition area, this will define our starting point. Also the Guiding Strip value, used in program Bend, of zero (0) conductors inside the guiding strip is used. This is because the inside group side and starting angles will already match the cross-section exactly. Program Bend defines the guiding as the least-strain surface in the group and stacks conductors on either side of it as specified by the user. The mid-point, of our 50-meter cable, is clamped to the inner layer center transition piece. This center transition piece is mounted to the mandrel of the coil-winding machine. Our cross-section drawing reviles that conductor No. 29 will be placed in the starting point. The conductor cable is a keystone shape and the Roxie data calls out the coordinates of each of its four corner points.

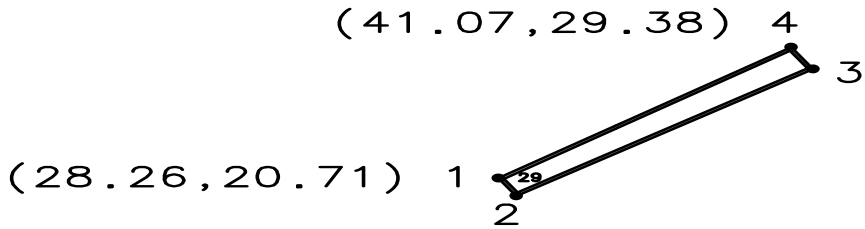

Figure 5: Cable cross-section.

We can now create a table with the following information for the Inner Layer.

Table 1:Conductor identification

CONDUCTOR GROUP NAME	CONDUCTOR NUMBER	NUMBER OF CONDUCTORS
ill1	29	1
ilr1	28	1
ill2	28	1
ilr2	27	1
ill3	27	11
ilr3	26	11
ir1	29	2
ir2	27	12

With the selected conductor number we can obtain the coordinates of the corner points from the Roxie data sheet. Using program ‘Angles’ enter the values of X1, Y1 on the inner radius. Then enter the values of X4, Y4 on the outer radius. Then enter the value of the outer radius. The program will output the ‘Initial edge angle’ and’ the

‘Outer starting angle’ values. Program Angles was developed for dipole magnet construction, there for 45 degrees must be subtracted from the calculated results.

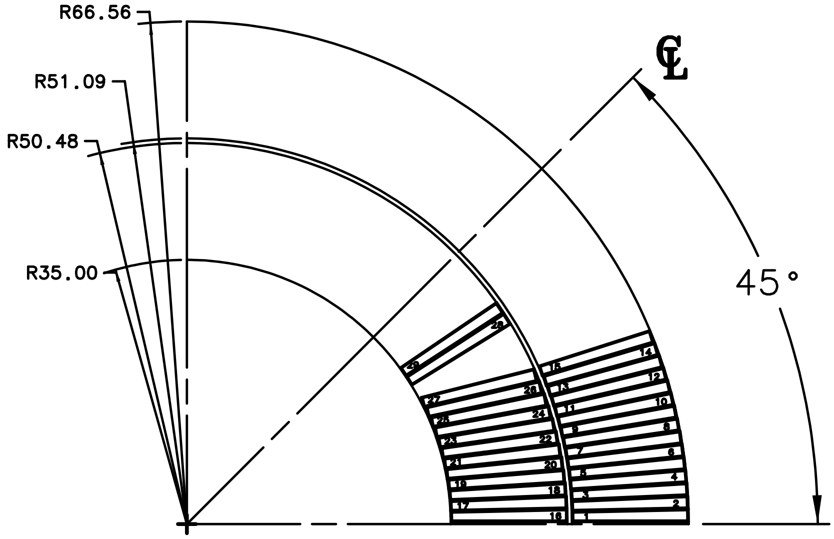

Figure 6: Cross-section view for angle calculations.

Angles for Inner Layer
Conductor Group #3.
There are 2 conductors.
The inner radius of the block is 35.0 mm.
The conductor number is 29.
Cable Height (insulated) 15.478 mm.

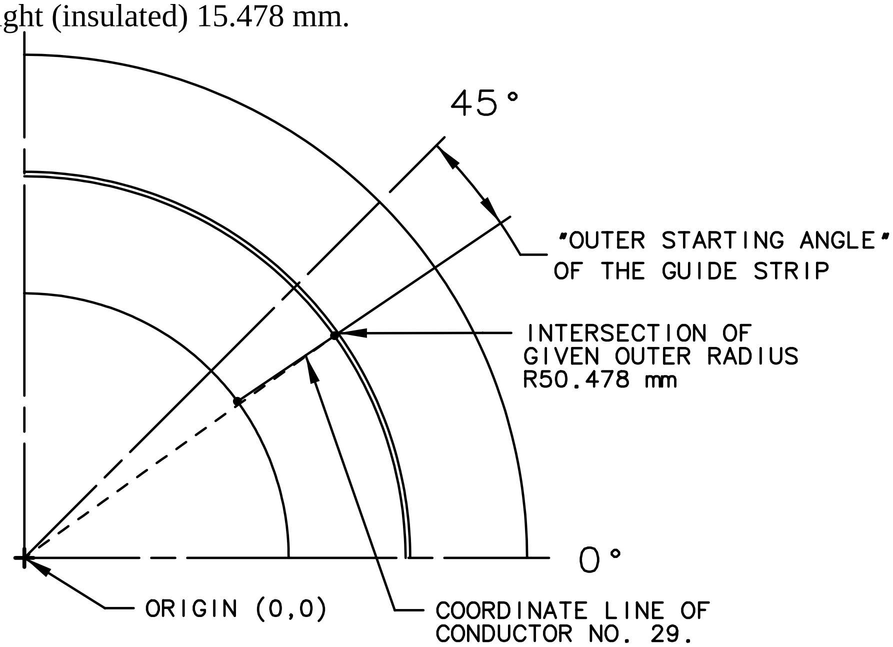

Figure 7: Cross-section view for Outer Starting Angle.

Program Angles extends and trims the coordinate line to the intersection of the Outer radius and to the origin (0,0). This is where the 'Outer Starting Angle' is measured from, the initial zero line is the 45 degree line. See Figure 7.

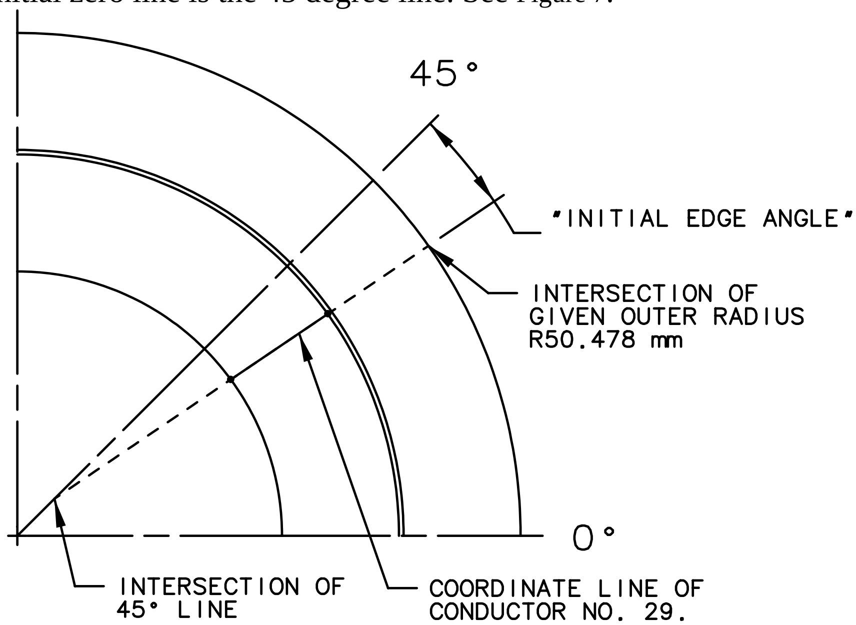

Figure 8: Cross-section view for Initial Edge Angle.

The Initial Edge Angle is measured from the 45-degree line to where the intersection of the coordinate line is located. See Figure 8.

Run Program Angle, example for conductor no. 29.

Enter the values of X1, Y1 on the inner radius.
X1 = 28.260 Y1 = 20.713
X4 = 41.079 Y4 = 29.389
Outer Radius = 50.478
Here are the results
Initial edge angle = 55.911 – 45 = 10.911
Outer starting angle = 54.418 – 45 = 9.418

Some additional cable dimensions, which are required to write the .xin, files, for program bend.
Calculate the Mid-Thickness of the cable.
Cable inner width (mm), (insulated) = 1.4165.
Cable outer width (mm), (insulated) = 1.7345.
1.7345 – 1.4165 = .318
.318 /2 = .159
1.4165 + .159 = 1.5755
Mid-Thickness of the cable is = 1.5755
The keystone angle of the cable is:
Tan x = .318/15.478 = .020545 atan (.020544) = 1.176976 degrees

We continue to calculate the Initial edge angle and the Outer-starting angle for the Inner Layer conductors.

Table 2: Inner layer angles

CONDUCTOR NO.	INITIAL EDGE ANGLE	OUTER STARTING ANGLE	OUTER RADIUS
29	10.911	9.418	50.478
28	12.088	11.387	50.478
27	30.875	20.923	50.478
26	32.052	22.923	50.478

Table 3: Outer layer angles

CONDUCTIOR NO.	INITIAL EDGE ANGLE	OUTER STARTING ANGLE	OUTER RADIUS
15	27.344	22.328	66.564
14	28.521	23.828	66.564

Transition angle:

Conduction no. 29, with insulation, is the transition from the inner layer to the outer layer. A drawing, using Ideas software was made to determine the four (4) corners coordinated points. They are as follows.

Table 4: Transition cable coordinates

X1 = 41.66790	X2 = 42.44973	X3 = 55.44443	X4 = 54.48710
Y1 = 29.58777	Y2 = 28.40655	Y3 = 36.81675	Y4 = 38.26314

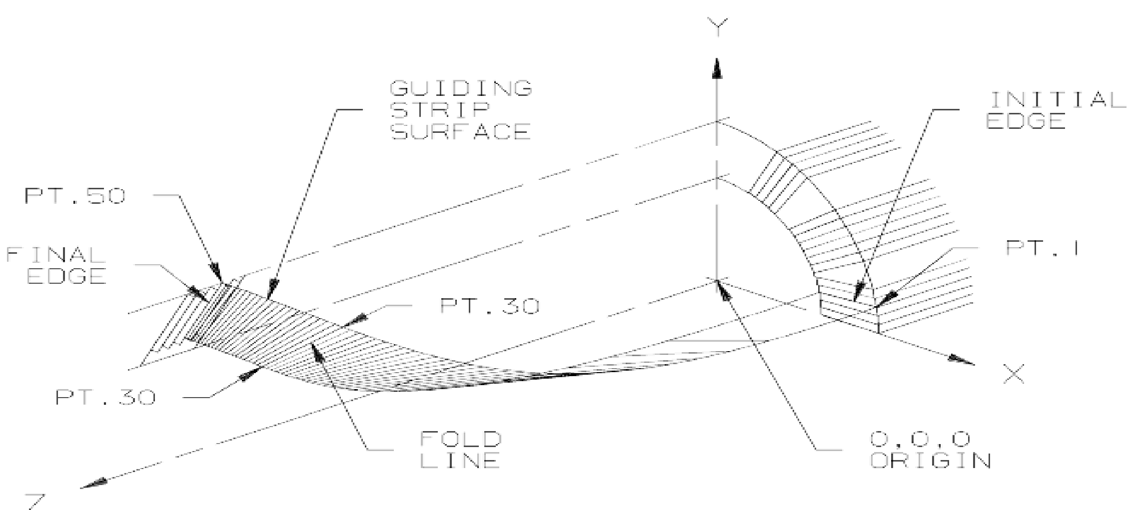

Figure 9: Location of the Initial Edge Angle in the coil.

Let us continue with some addition naming requirements, which will be of the Inner Layer, Lead End parts. From our initial sketch we have determined that there will be four (4) lead end parts. They are named as follows.

Table 5: Inner layer, lead end, and part names.

PART NO.	NAME	LEFT SIDE	RIGHT SIDE
411355	ilkey	ill1.ins	ilr1.ins
411356	ilspacer1	ill1.ous ill2.ins	ilr1.ous ilr2.ins
411357	ilspacer2	ill2.ous ill3.ins	ilr2.ous ilr3.ins
411358	ilsaddle	ill3.ous	ilr3.ous

Note: .ins means this file is for an inside surface. . ous means this file is for an outside surface and il stands for 'inner lead'.

End Part names for the Inner Layer, Return End. Return end parts are symmetrical.

Table 6: Inner layer, return end, and part names.

PART NO.	NAME	LEFT AND RIGHT SIDES
411352	irkey	ir1.ins
411353	irspacer1	ir1.ous ir2.ins
411354	irsaddle	r2.ous

Table 7: Outer layer, lead end, and part names.

PART NO.	NAME	LEFT SIDE	RIGHT SIDE
411361	olkey	oll1.ins	olr1.ins
411362	olspacer1	oll1.ous oll2.ins	olr1.ous olr2.ins
411363	olsaddle	oll2.ous	olr2.ous

Table 8: Outer layer, return end, and part names.

PART NO.	NAME	LEFT AND RIGHT SIDES
411359	orkey	or1.ins
411360	orsaddle	or1.ous

We now have the necessary data to create our Bend input files (.xin). Individual files will be written for each End part. Here is our example for conductor no. 29. The important A-Length variable can be graphed in Excel to show its relationship to final edge angle of the guiding strip. To select a starting value for the A-length we can make it at least as large as the part inside the group is wide. Lets create a Bend input file. Notepad works just fine.

Nb3Sn IRQ, 70mm bore: ill1-inside layer, 3rd conductor group. 12/17/2002

50.478	outer radius
35.0	inner radius
9.418448	outer starting angle of the guiding strip
10.91187	initial edge angle of the guiding strip
1.5755	mid-thickness of the cable
1.1769	keystone angle of the cable\
0.0	rounding of corners of the cable
0 1	number of cables on each side of the guiding strip
1	choose inside group A-length
15	A-length
N	do not choose the final edge angle of the guiding strip
7.74	estimated final edge angle of the guiding strip
	Conductor no. 29, LEAD END, ill1.xin

Save the file as, ill1.xin

Lets run program Bend.

Open a Unix window.
Enter Bend
Enter 1 space 3 carriage return.
Enter the complete file name for the disk file from which the input file is to be read. This file was just created above, ill1.xin.
Enter the file name for all output. disk files.
Use the naming convention: i = inner layer. r = return end. 1 = first conductor group. This example of the file output name would be: ill1. (Include no file type or separating period).
ill1
Accept the guiding strip width default value.
What angle would you prefer (degrees)? Accept the final edge angle of the guiding strip calculated by the program or enter the angle you prefer.
Enter 7.74
The inside group A-length is now 15.000, OK? (N/Y)
Enter a carriage return to accept the selected angle.
Expansion, enter the default.
Shift = 0
Bluntness = .3

Enter NO for: Do you want to try different values of shift, bluntness, etc.? (N/Y)
Enter NO for: Do you want centroids of the current density of the cables?
Enter YES for: Do you want the corners of the cable?
Enter YES for: Do you want all the cable frames?
Enter a carriage return for all the WARNINGS.
Enter NO for: Do you want a shelf under this group?
Enter YES for: Do you want the inside lateral surface?
Enter YES for: Do you want the outside lateral surface?
Enter NO for: Do you want to continue with interactive control over…
Enter NO for. Free edges.
Remember for the Lead End you need the left side and the right side data files. These files will have an ‘l’=left or ‘r’=right add to the file output name. The Return End is symmetrical about the centerline.
Use control ‘C’ to abort the program.

Run program Bend with the following A-Length values to obtain the programs calculated inclination Angle. Our example file, ill1.xin, will have to have the A-length value edited for each run.

Table 9: A-Length vs. Inclination Angle for ill1.xin

A-Length	Inclination Angle
5	16.598
10	8.2860
13	7.7671
15	7.7487
18	7.7479
20	7.7478

We will enter this data into Excel to produce the following graph.

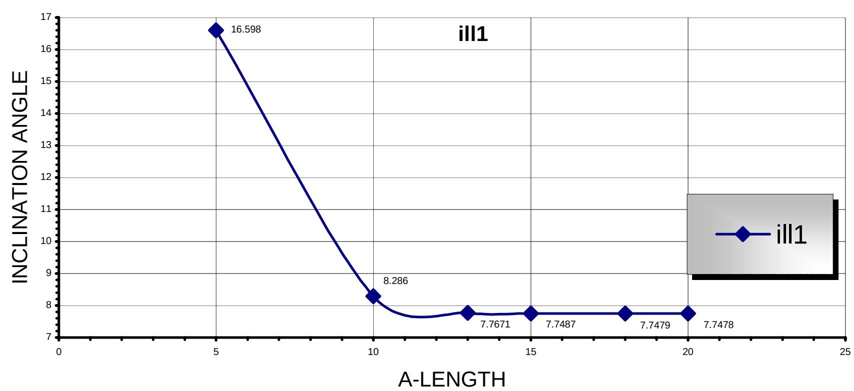

Figure 10: Excel plot of the Inner layer, Lead end, A-lengths and Inclination angles.

Here is the Bend program run.

```
 This is version April 14, 1994 of Program BEND,
 Last modified on March 6, 1995.

 Please enter, on one line, the numbers of only those
 Options that you want to change from the default.

           Option                    Default     Alternate
  ------------------------------  ---------      -----------
  1 Input from an external file:  No         Yes
  2 Output to a journal file:      No         Yes
  3  Units:                        British     SI
  4  Perturb group:                No         Yes
  5  Cable cross section:          Unchanged   Change
  6  Steepen rulings:              No         Yes
  7  Automatic:                    No         Yes
  8  Vary the base curve:          No         Yes
  9  Verbose terminal I/O:         No         Yes
 10  Debug:                        No         Yes
 11  Help:                         No         Yes

1 3

  Please enter the complete file name for the disk file from which input is to be
 read. (Include the file type and, if necessary, the version number,
 with the separating punctuation "." and ";".)
ill1.xin

  The title of the input file is:
  Nb3Sn IRQ, 70 mm bore:ill1-Inside layer, 3rd conductor group:06/19/02

 Lengths will be measured in millimeters during
 input and output, but internal units are SI.

 Please enter the file name for all output disk files.
 (Include no file type or separating period).
ill1

 The radius of the cylinder on which the base curve is wound
 is  50.478000 millimeters,
 and the radius of the mandrel is  35.000000 millimeters.
 The width of the guiding strip is now  15.4780 millimeters, the difference
 of these two numbers. What value would you prefer?

 The outer starting angle for the guiding strip is  9.41848014 degrees.
The initial edge angle of the guiding strip is 10.91187780 degrees.
```

The mid-thickness of the cable is 1.57550.
The (uncorrected) keystone angle is 1.17697600 degrees.
The radius of curvature of corner rounding is 0.000000.
There will be 0 cables inside the guiding strip and 1 outside.
The desired inside group A-length is 15.000000000000
The estimate of the final edge angle of the guiding strip is, in degrees,
7.7400000000000
An initial guess at the guiding strip A-length is 15.00000 millimeters.
The final edge angle of the guiding strip is now 7.7488045894487 degrees.
What angle would you prefer (degrees)?
7.74
(There will be a slight change from the initially prescribed A-length.)

The twist-spline starts at point number 2.
The overall Delta-L-Over-L is -0.0127.

Y-Z cross section cut by the vertical midplane at X = 0:

Lateral Surface:	Inside		Outside		
	Z	Y	Z	Y	
At outer radius:	15.0000000	50.4780000	16.8445521	50.4780000	mm,
At inner radius:	17.1037120	35.0000000	18.9175137	35.0000000	mm,

Final edge angles: 7.74000000000 7.62820485042 degrees,

"A" Lengths: 15.00000000000 16.84455211345 mm.

The inside group A-length is now 15.00000000000, OK? (N/Y)
y

The accepted value for the guiding strip A-length is
15.0000000000 millimeters.

The length of the base curve is 19.32 millimeters.
The length of the free edge is 19.32 millimeters.
The total twist of the developable strip is -13.00 degrees.
The final edge angle of the guiding strip is now 7.7400000000000 degrees.
What angle would you prefer (degrees)?

The total twist of the guiding strip is now -14.49 degrees.

The distribution of the twist angle is now given by
an expansion of amount 0.000
and a shift of amount 0.000
and added bluntness of 0.000.
What values would you prefer for:

Expansion?

Shift?
0
Bluntness?
.3
with narrowness?

Expansion = 0.000, fixed point = 0.500
shift = 0.000 and bluntness = 0.300
with narrowness 0.000

The twist-spline starts at point number 2.
The overall Delta-L-Over-L is 0.0066.

Step Number	Length (Base)	Delta-L -Over-L	Phi	Curve Rad (Base)	Curve Rad (Free)	Twist Rate	Alpha
1	0.0000	-0.0026	1.49	233.17	408.96	0.0	90.00
2	3.8514	-0.0088	1.45	53.92	112.72	-0.1	93.51
3	4.8172	-0.0102	1.36	26.79	64.06	-0.3	94.95
4	5.5785	*-0.0105	1.24	21.94	49.19	-0.5	96.04
5	6.2276	-0.0098	1.10	19.07	40.94	-0.6	96.94
10	8.6826	0.0034	0.19	12.88	21.42	-1.2	99.94
15	10.5297	0.0232	-0.73	10.45	10.07	-1.6	101.48
16	10.8595	0.0265	-0.87	10.12	8.60	* -1.6	101.65
20	12.0886	0.0367	-1.19	9.10	5.22	-1.4	101.93
25	13.4759	0.0463	-0.99	8.23	4.47	-1.1	101.47
26	13.7385	* 0.0466	-0.90	8.10	4.56	-1.1	101.27
30	14.7510	0.0396	-0.53	7.65	5.11	-1.0	100.20
40	17.0989	0.0067	-0.05	7.00	3.48	-0.8	95.81
48	18.8787	-0.0014	0.01	6.81	* 2.04	-0.2	91.21
50	19.3191	------	0.01	10.09	2.92	0.0	90.00

Do you want to try different values of shift, bluntness, etc.? (N/Y)
n

Do you want the centroids of the current densities
in the cables? (N/Y)
n
Do you want the corners of the cables? (N/Y)
n
Do you want all of the cable frames? (N/Y)
n

********************** WARNING **********************

There is a reversal of direction among the three coordinates (X, Y, and Z) of the four curves (inside inner, inside-outer, outside-inner, and outside-outer) determining the configuration of the group of cables:

Side	Radii	Coord	Point	Extremum	Type
Inside	Inner	Y	36	34.911022	Maximum
Inside	Inner	Y	50	34.896748	Final

ANALYSIS

---------------- On the inside lateral surface of the group ----------------

The length of the outer curve is 19.3191 mm.
Its worst curvature occurs at point number 49, 19.099 mm along the arc,
where its radius of curvature is 6.805 mm.
The length of the inner curve is 19.4517 mm.
Its worst curvature occurs at point number 48, 19.343 mm along the arc,
where its radius of curvature is 1.870 mm.
The overall Delta-L-Over-L of this surface is 0.0069.
The lowest Delta-L-Over-L is -0.1016 at point 50,
19.3191 mm along the outer curve.
The highest Delta-L-Over-L is 0.0371 at point 22,
12.6600 mm along the outer curve.

---------------- On the outside lateral surface of the group ----------------

The length of the outer curve is 22.1882 mm.
Its worst curvature occurs at point number 48, 21.6296 mm along the arc,
where its radius of curvature is 8.557 mm.
The length of the inner curve is 22.2413 mm.
Its worst curvature occurs at point number 50, 22.2413 mm along the arc,
where its radius of curvature is 1.940 mm.
The overall Delta-L-Over-L of this surface is 0.0024.
The lowest Delta-L-Over-L is -0.2228 at point 6,
7.0838 mm along the outer curve.
The highest Delta-L-Over-L is 0.0788 at point 4,
5.7460 mm along the outer curve.

(There are no cables internal to the group.)

Y-Z cross section cut by the vertical midplane at X = 0:

Lateral Surface: Inside Outside

```
                       ---------------------        ---------------------
                          Z          Y          Z          Y
 At outer radius:  15.0000000  50.4780000   16.8445521   50.4780000  mm,
At inner radius:  17.1037120   35.0000000   18.9175137   35.0000000  mm,

 Final edge angles:     7.74000000000        7.62820485042     degrees,

"A" Lengths:        15.00000000000       16.84455211345     mm.

X-Y cross section cut by the transverse plane at Z = 0:

 Lateral Surface:             Inside                   Outside
                         ---------------------      ---------------------
                          X             Y           X            Y
At outer radius:      8.2604300    49.7975279    9.9670383   49.4842059   mm,
Starting angles:      9.4184801           11.3880635       degrees,
At inner radius:      5.3290238    34.5919283    6.7251567   34.3478131   mm,
Starting angles:      8.7577935           11.0781268       degrees,

Side angles:        10.9118778          12.0888538       degrees.

 Do you want a shelf under this group? (N/Y)
n
 Do you want the inside lateral surface of this group? (N/Y)
y
 Do you want the outside lateral surface of this group? (N/Y)
y

 File ill1.ins has been created.

 File ill1.ous has been created.

 Do you want to continue, with interactive control
 over variation of the free edge? (N/Y)
n
 Do you want automatic control over variation
 of the free edge? (N/Y)
n
 ********* Normal completion of program BEND *********
STOP:
```

From the Excel graph of Inclination Angle vs. A-length, for conductor no. 29, we see that as A-length increases the inclination angle approaches a value near 7.747. We then choose the A-length value of 15. This is where the inclination angle begins to asymptote to a constant.

We write the following input file name, .xin files, and run program Bend for each A-Length increment. We record the resulting inclination angles and produce an Excel graph of all the plots.

Table 10: File name and A-Length increment range .

Input File Name	Conductor Number	Number of Cables on each Side of Guide-Strip	A-Length Range X 5 Increments
ill1.xin	29	0 1	5-20
ilr1.xin	28	0 1	5-20
ill2.xin	28	0 1	5-25
ilr2.xin	27	0 1	15-30
ill3.xin	27	0 11	15-35
ilr3.xin	26	0 11	15-35
ir1.xin	29	0 2	5-25
ir2.xin	27	0 12	15-35
oll1.xin	15	0 1	15-35
olr1.xin	29	0 1	15-30
oll2.xin	14	0 10	30-50
olr2.xin	15	0 14	30-50
or1.xin	15	0 15	20-45

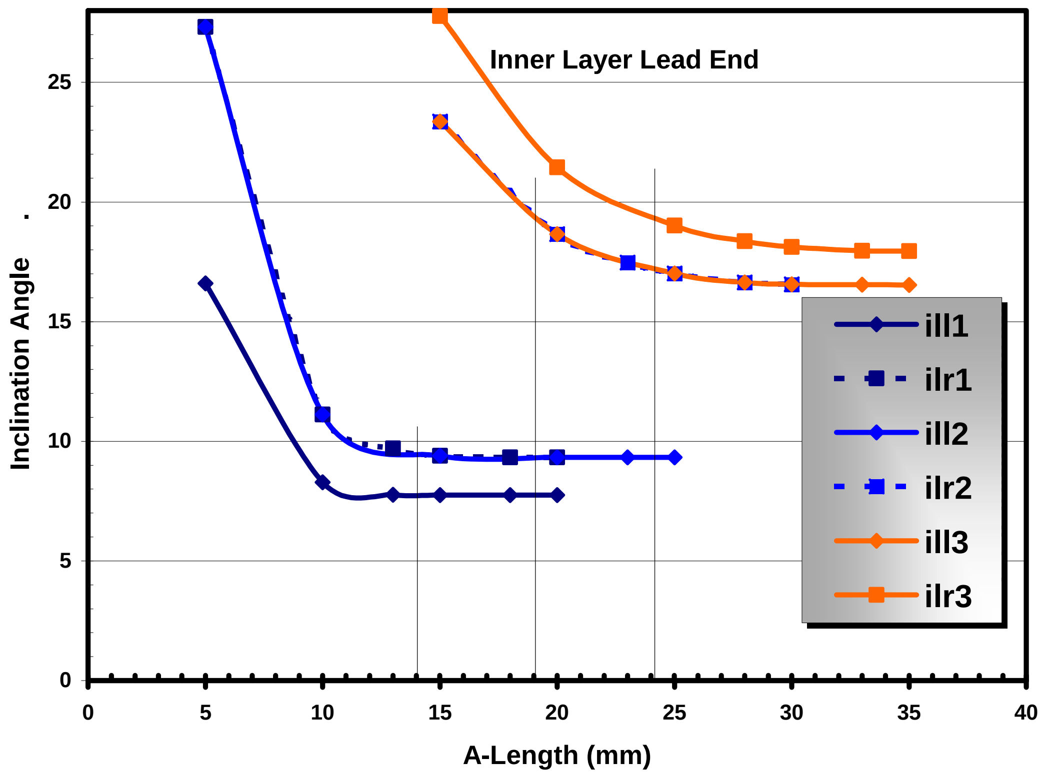

Figure 11: Excel plot of the Inner Layer, Lead end, A-lengths and Inclination angles.

Table 11: Inner layer, Lead end, Inclination angle (in degrees) vs. A-length, (in mm).

ill1			ill2			ill3	
5	16.598		5	27.32		15	23.362
10	8.286		10	11.124		20	18.657
13	7.7671		15	9.39		25	17.0116
15	7.7487		20	9.3229		30	16.5574
18	7.7479		23	9.3226		33	16.5399
20	7.7478		25	9.3225		35	16.5384
ilr1			ilr2			ilr3	
5	27.32		15	23.3624		15	27.772
10	11.1243		20	18.657		20	21.4449
13	9.7014		23	17.4679		25	19.0128
15	9.39		25	17.0116		30	18.1206
18	9.3238		28	16.6424		33	17.9677
20	9.3229		30	16.5574		35	17.9518

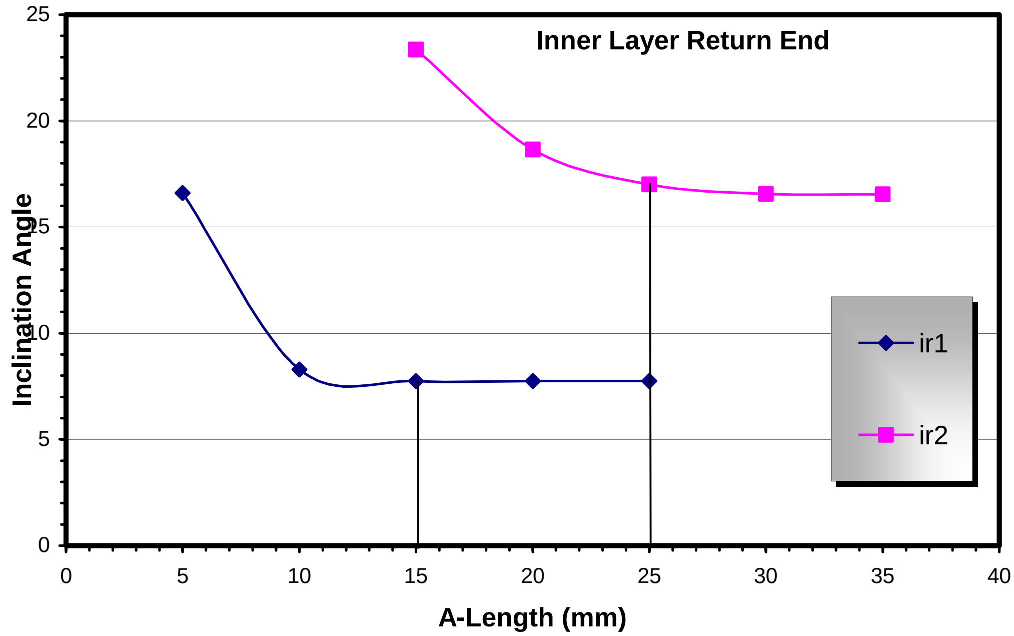

Figure 12: Excel plot of the Inner Layer, Return end, A-lengths and Inclination angles.

Table 12: Inner layer, Return end, and data. A-length in mm, Inclination angles in degrees.

ir1			ir2	
5	16.5983		15	23.3624
10	8.286		20	18.657
15	7.7488		25	17.0116
20	7.7478		30	16.5574
25	7.7478		35	16.5384

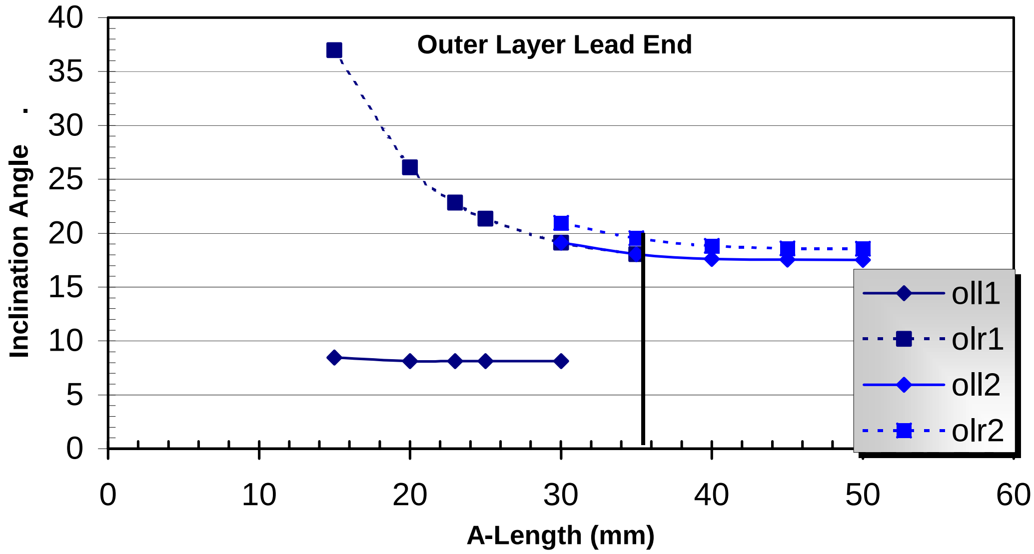

Figure 13: Excel plot of the Outer Layer, Lead end, A-lengths and Inclination angles.

Table 13:Outer layer, Lead end, and data. A-length in mm, Inclination angles in degrees.

oll1			**oll2**	
15	8.4676		30	19.1225
20	8.1512		35	18.0582
23	8.1496		40	17.6176
25	8.1494		45	17.5369
30	8.1493		50	17.5328
olr1			**olr2**	
15	36.9597		30	20.9543
20	26.1068		35	19.5255
23	22.8304		40	18.8409
25	21.3597		45	18.5969
30	19.1225		50	18.5735
35	18.0582			

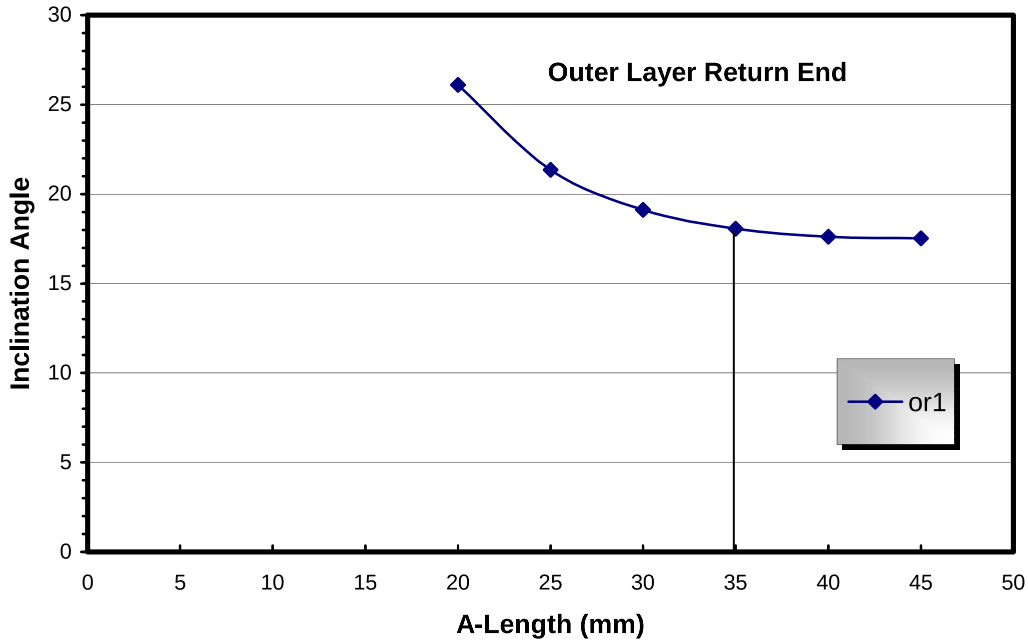

Figure 14: Excel plot of the Outer Layer, Return end, A-lengths and Inclination angles.

Table 14: Outer layer, Return end, and data, A-lengths in mm, Inclination angles in degrees.

or1	
20	26.1068
25	21.3597
30	19.1225
35	18.0582
40	17.6176
45	17.5369

Origin offset differences.

The straight section of the coil has its origin aligned with the centerline of the beam tube. To minimize magnetic field disturbances, in the end parts, the origin of selected end groups can be shifted away from the origin (0,0,0). Translating the origin, of the end part along the z-axis will result in the lengthening of the straight section of that current block. Origin offset is performed when using program “Part.exe”. Origin differences of individual surfaces can be used to help in reducing bulges in the cable.

A-Length hints.

1.) Large A-Length values produces bulges.
2.) Short A-Length values won’t let the twist in the cable group be evenly spread out along the curve.
3.) Lead end A-Lengths should be the same on the return end as on the lead end.
4.) Lead end parts have left and right sides; the inclination angles must be the same.
5.) Use determined A-Lengths close to the suggested angle calculated by the program “Bend”.
6.) Use short A-Lengths to keep the over all length of the ends as short as possible.

Shift and Blunt variables.

To optimize our design we can begin with the following parameters.

1.) **Shift;** use values from –2 to 2. Shift is used to change the spread of twist [1].
2.) **Different values of Shift,** from a range of –2 to 0, by 50 increments produce different values of delta L/L. We want to use small values of delta L/L. So select the Shift value, which produces the smallest value of delta L/L. Hold, the blunt value fixed at zero (0).
3.) **Blunt,** use values from 0 to 0.5. Holding the Shift value fixed at the selected minimums. Blunt is used to change the radius of curvature. [1]
4.) **Minimize Delta L / L,** generally below –0.3. The value in the chart is a negative value, even though it does not show the negative sign.
5.) **Maximize Radius of curvature,** minimum approx. 10mm. This is important for the inner layer pole piece. Pick values, which increase the Radius of curvature.
6.) **Shift and Blunt values** can be different for left and right sides of the Lead end parts.
7.) **Create Excel charts;** a graphical representation of the group’s surfaces is produced using a macro to automate the process.

Put it together.

From our determined A-Lengths and Inclination angles we can run program Bend and find the optimum Shift and Blunt values. When the desired values are acceptable then select Yes to the creation of the inside lateral surface and the outside lateral surface. We will now have files with the extension .ins and .ous.

Table 15: Bend design parameters for the Inner layer, Lead end.

Input File	A-Length	YZ Inclination Angle	Bend Suggested Angle	Delta |L/L|	Offset	Shift	Blunt
ill1.xin	15	7.74	7.748	0.083	0	0	0.3
ilr1.xin	15	7.74	9.390	0.060	0	0	0.3
ill2.xin	20	12	9.323	0.087	5	0	0.3
ilr2.xin	20	12	18.657	0.012	5	0	0.3
ill3.xin	25	17	17.012	0.413	2	-0.707	0.3
ilr3.xin	25	17	18.657	0.413	2	-0.707	0.3

Table 16: Bend design parameters for the Inner layer, Return end.

Input File	A-Length	YZ Inclination Angle	Bend Suggested Angle	Delta |L/L|	Offset	Shift	Blunt
ir1.xin	15	7.75	7.748	0.004	0	-0.384	0.258
ir2.xin	25	11	17.011	0.083	2	0.02	0.141

Table 17**:** Bend design parameters for the Outer layer, Lead end.

Input File	A-Length	YZ Inclination Angle	Bend Suggested Angle	Delta |L/L|	Offset	Shift	Blunt
oll1.xin	35	13	18.058	0.022	0	0	0.275
olr1.xin	35	13	18.149	0.037	0	0	0.275
oll2.xin	35	18.06	19.525	0.112	10	0	0.311
olr2.xin	35	18.06	18.058	0.092	10	0	0.158

Table 18: Bend design parameters for the Outer layer, Return end.

Input File	A-Length	YZ Inclination Angle	Bend Suggested Angle	Delta |L/L|	Offset	Shift	Blunt
or1.xin	35	18.06	18.058	0.017	0	0	0

Table 5, 6,7 and 8 gives us all the names of the files which program bend will create.

After creation of all the .ins and .ous files we will use the Excel macro to produce the following charts. The inside and outside surfaces, of each conductor group are now displayed. The Bend program generated data files were used to produce the Excel plots, which follows.

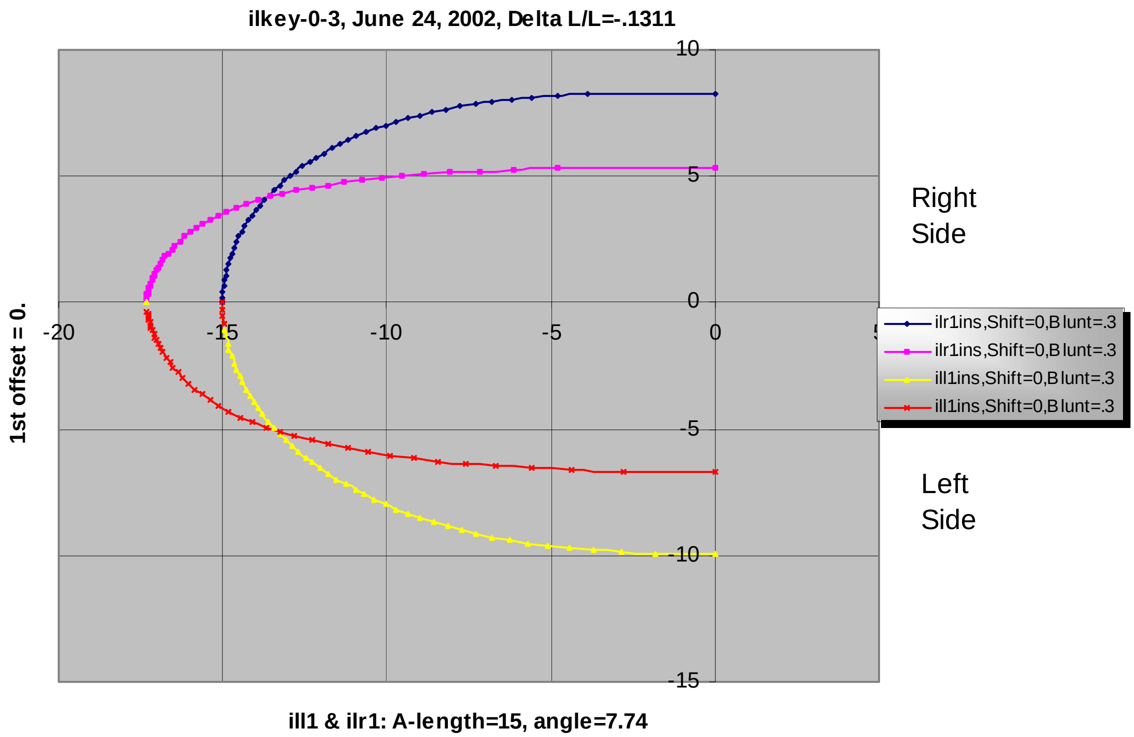

Figure 15: Inside surface for Inner layer ,Lead end, 3rd conductor group:

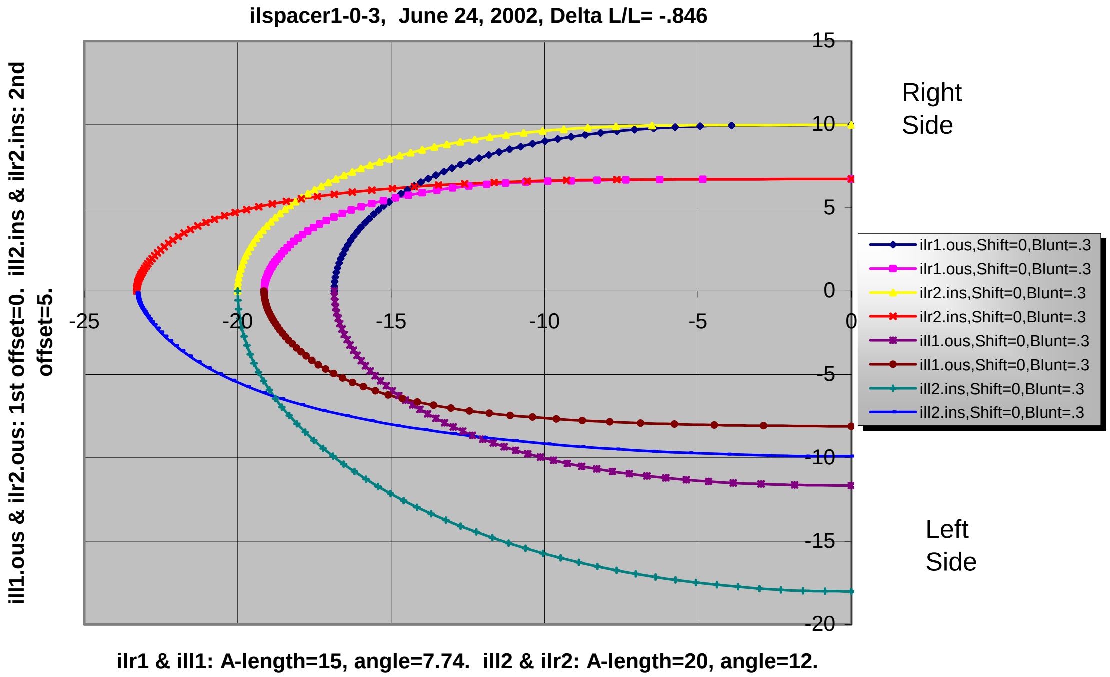

Figure 16: Inside surface for Inner layer, Lead end, ilspacer1.

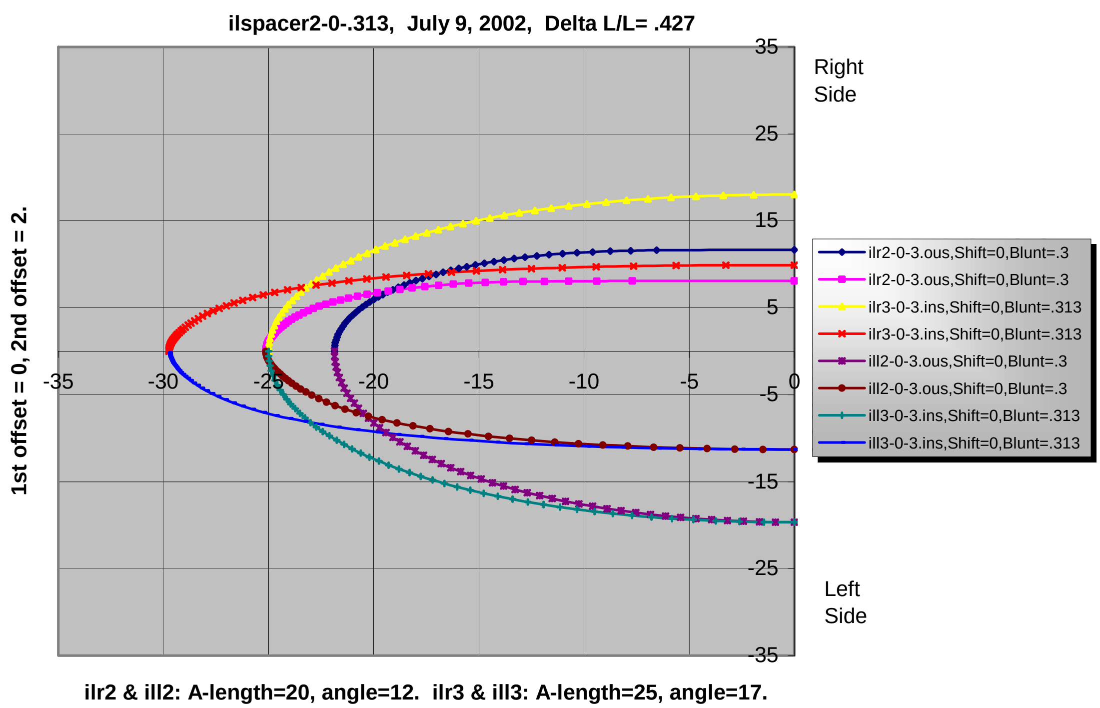

Figure 17: Inside surface for Inner layer, Lead end, ilspacer2.

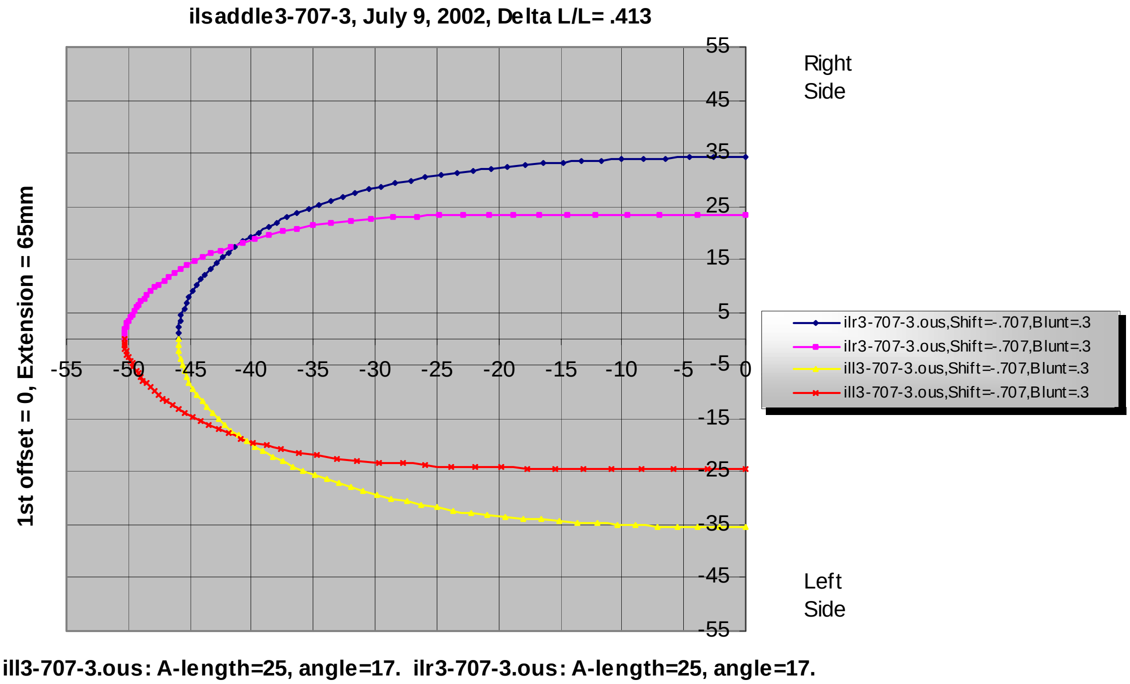

Figure 18: Inside surface for Inner layer, Lead end, ilsaddle.

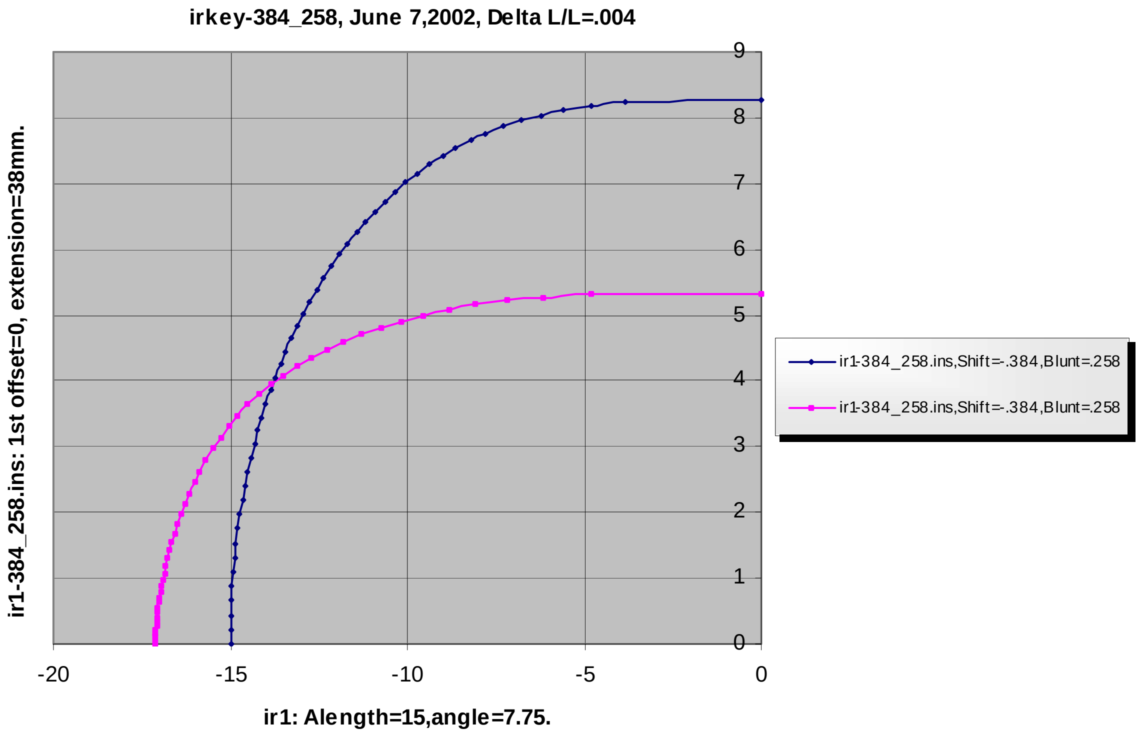

Figure 19: Inside surface for Inner layer, Return end, irkey. Part is symmetrical.

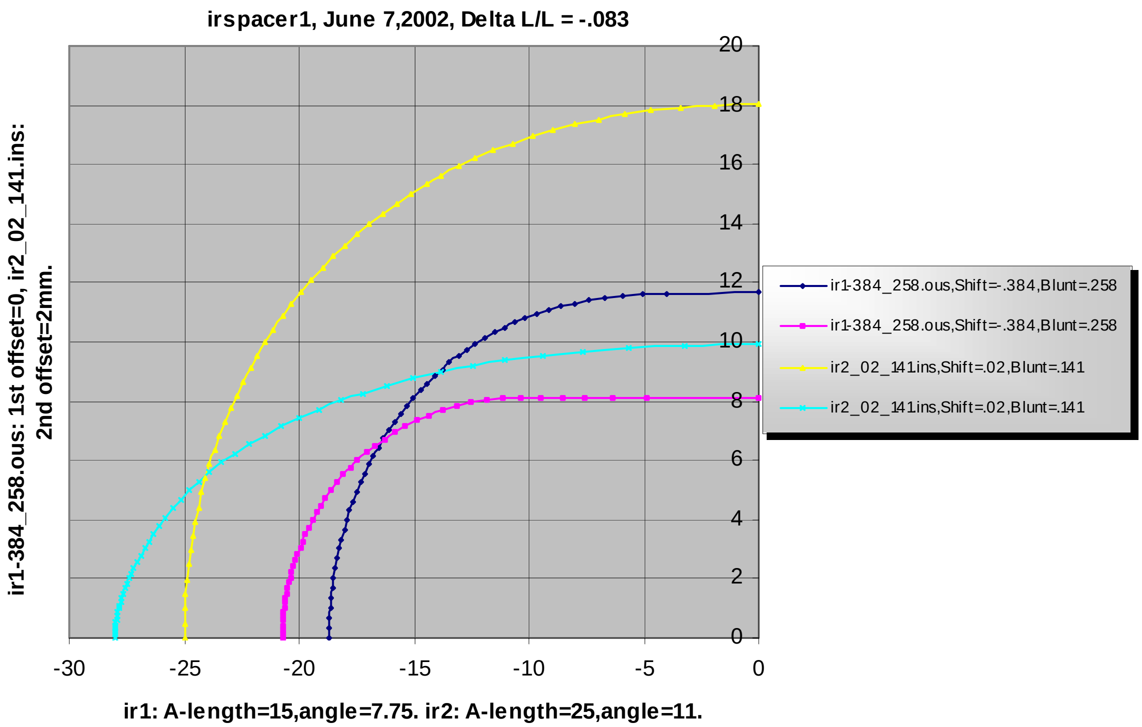

Figure 20**:** Inside and outside surface for Inner layer, Return end, irspacer1. Part is symmetrical.

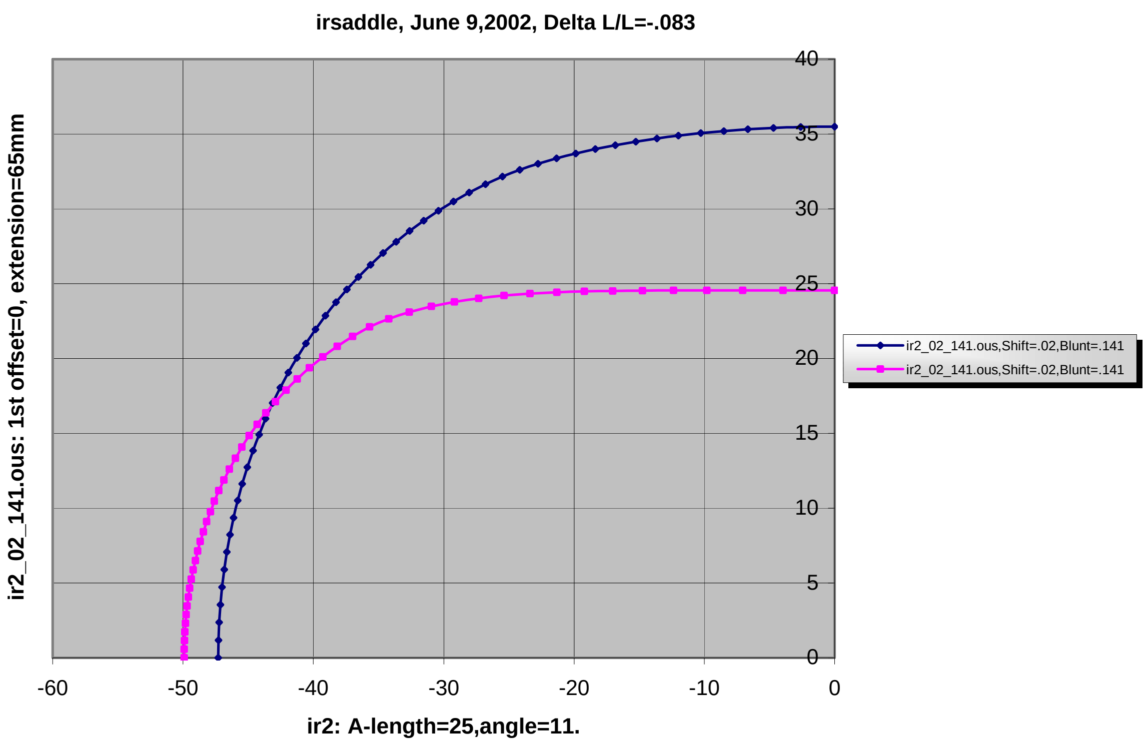

Figure 21: Inside surface for Inner layer, Return end irsaddle. Part is symmetrical.

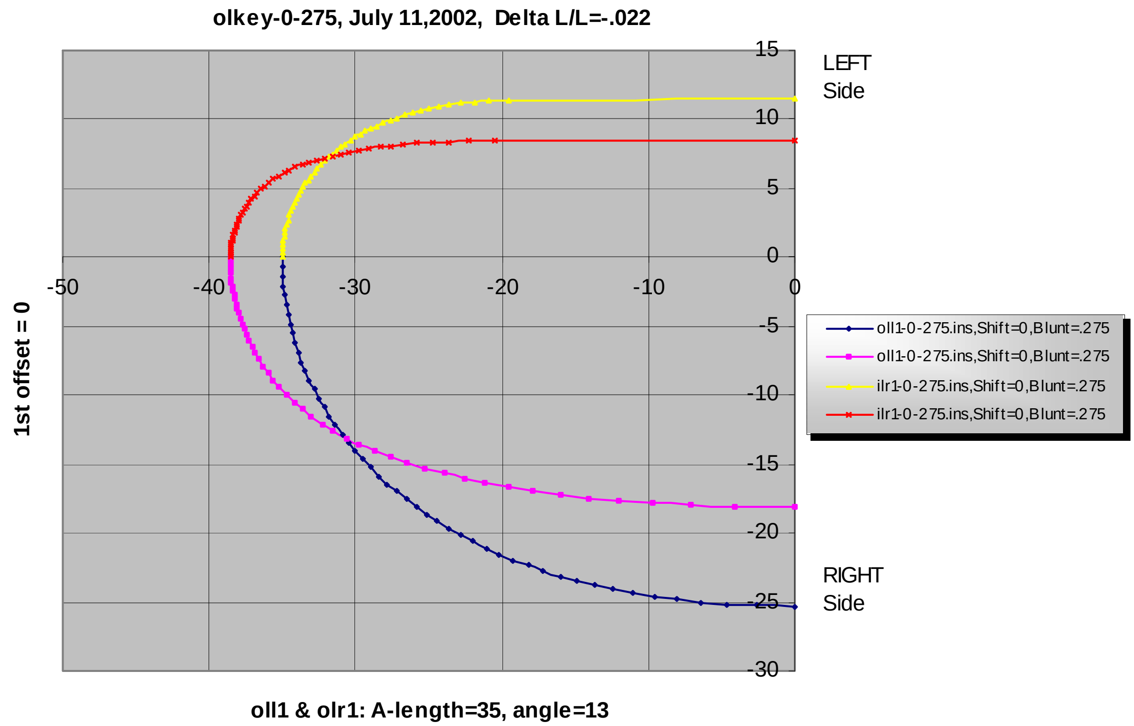

Figure 22**:** Outside surface for Outer layer, Lead end, olkey.

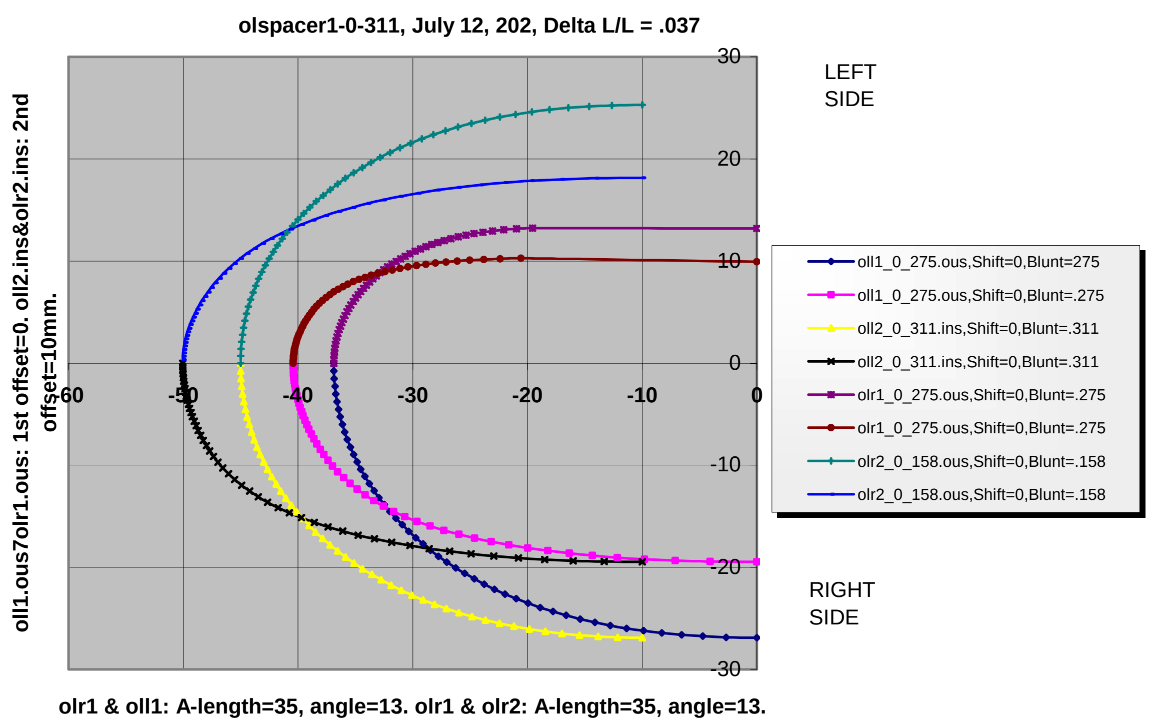

Figure 23: Inside and outside surface for Outer layer, Lead end, olspacer1.

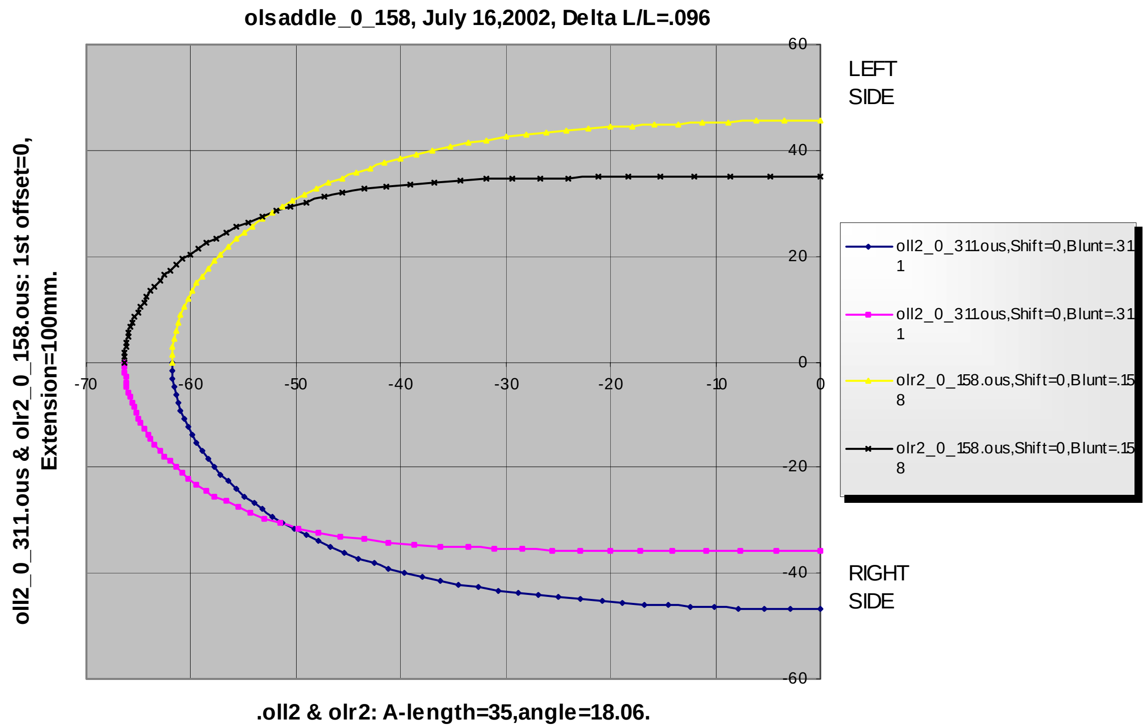

Figure 24: Inside surface for Outer layer, Lead end, olsaddle.

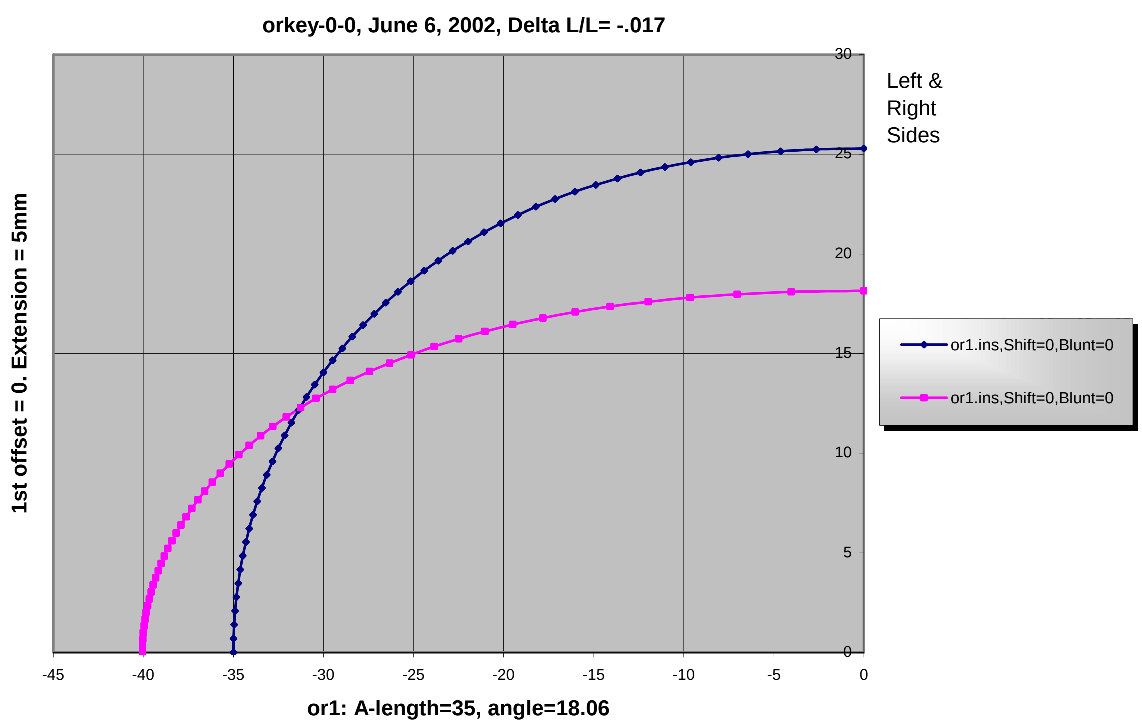

Figure 25: Outside surface for Outer layer, Return end, orkey. Part is symmetrical.

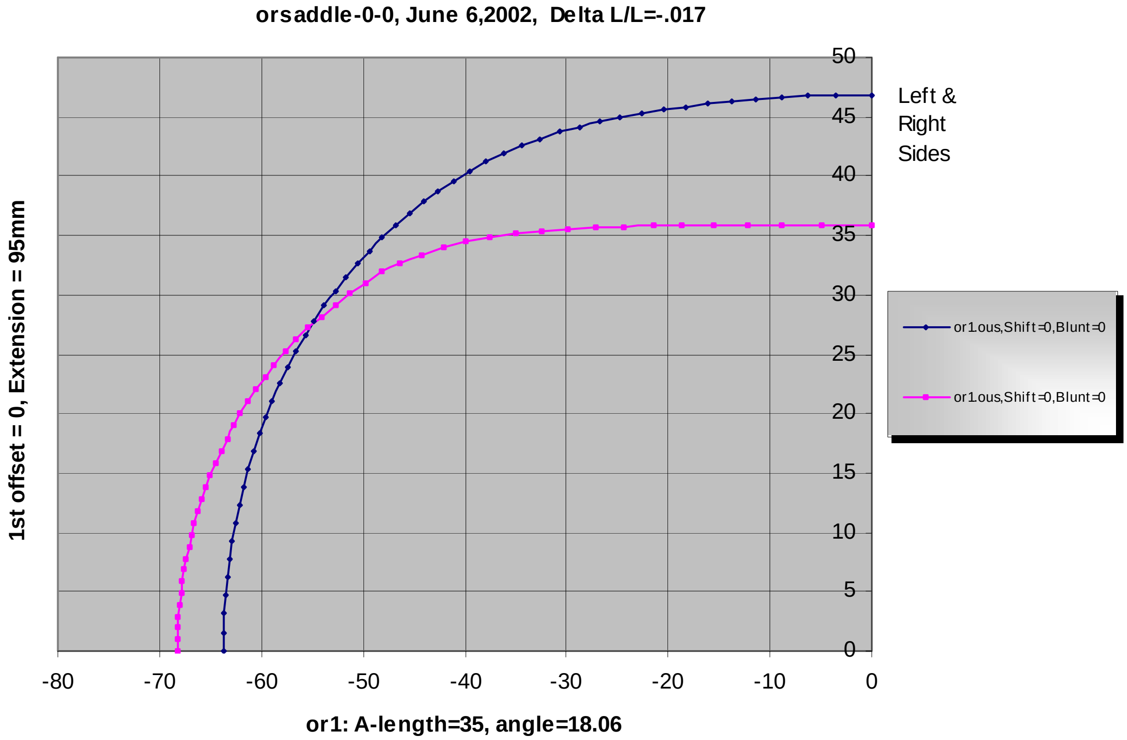

Figure 26: Inside surface for Outer layer, Return end, orsaddle. Part is symmetrical.

Final Bend output files.

When satisfactory Delta L/L values have been achieved and shift and blunt values produce acceptable curves have program 'Bend' output files with the extension of .cor and .fra. Do this for each .xin file.

DELCORD

This program sees the .cor file of a group to compute the Delta L/L's of each cable edge at each ruling. [2]
The steps for running 'Delcord' are as follows, then producing a chart in 'Excel'.

1.) Create .cor files in program 'Bend'.
2.) Open a Unix window and run 'DELCORD.exe'
3.) Enter filename, no extension delta L/L (count from the Guide Strip), 1=cable number.
4.) Cut data from run program (select data, edit, copy).
5.) Nedit, new file, create.
6.) Paste in data.
7.) Save.
8.) Open Excel.
9.) Import the data text file.
10.) Select the data in Excel.
11.) Open a new chart
12.) Select scatter, as the type of chart.
13.) Create chart with four (4) data lines.
14.) Name them, Outer near, Inner near, Outer far, Inner far.
15.) Save the chart.

Here are the 'DELCORD' charts.

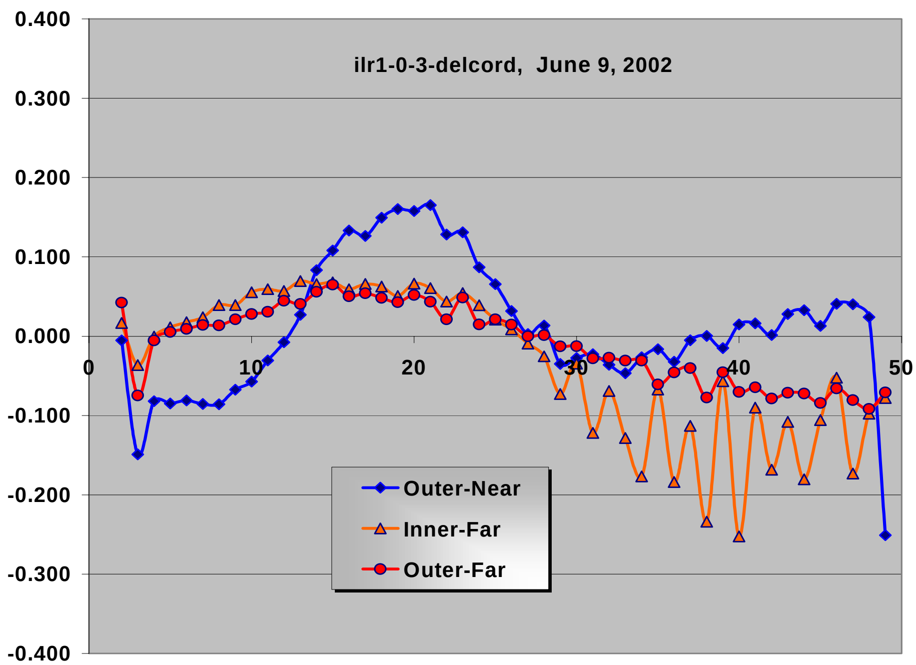

Figure 27: Delcord output for ilr1-0-3.

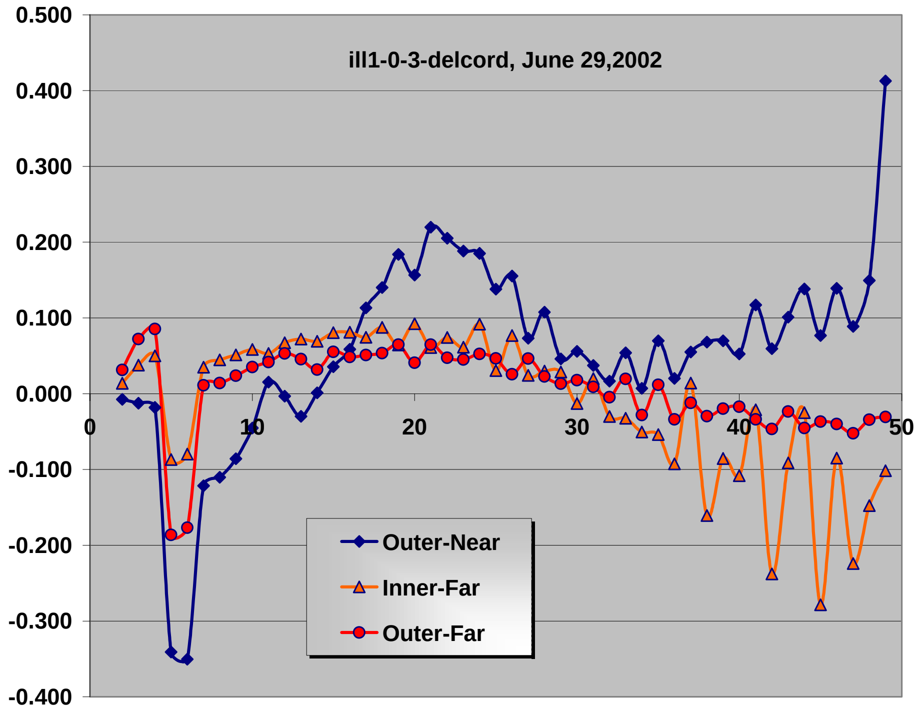

Figure 28: Delcord output for ill1-0-3.

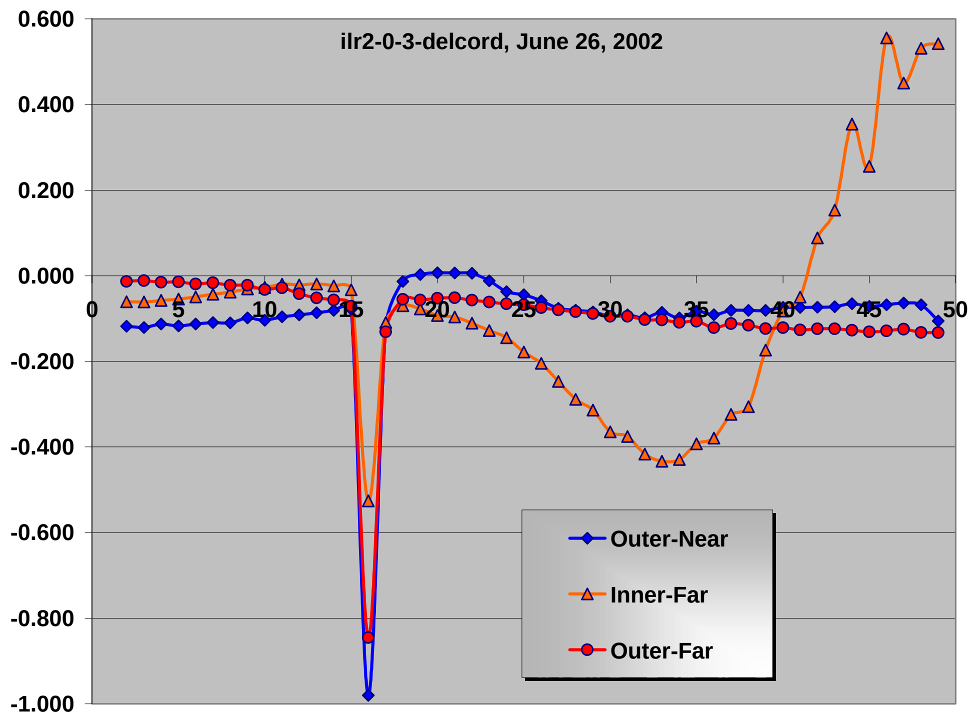

Figure 29: Delcord output for ilr2-0-3.

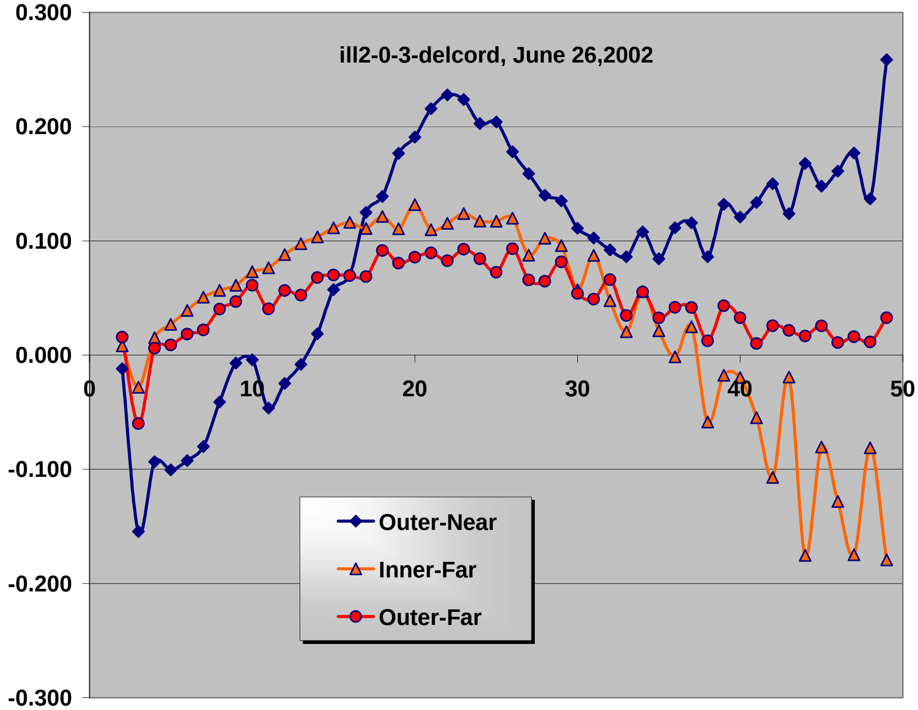

Figure 30: Delcord output for ill2-0-3.

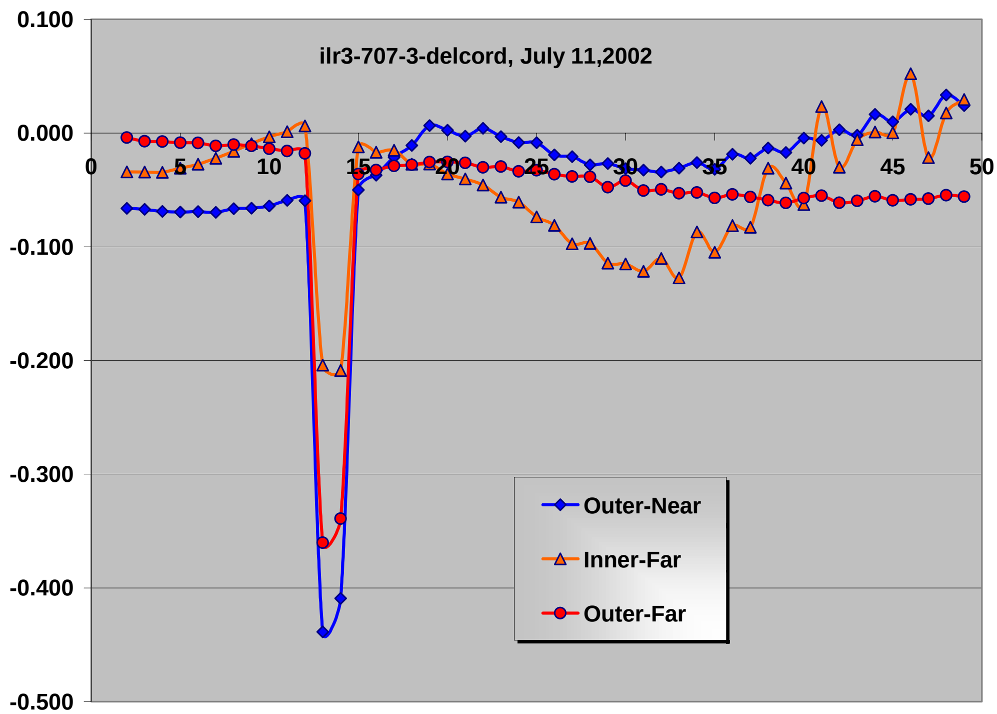

Figure 31: Delcord output for ilr3-707-3.

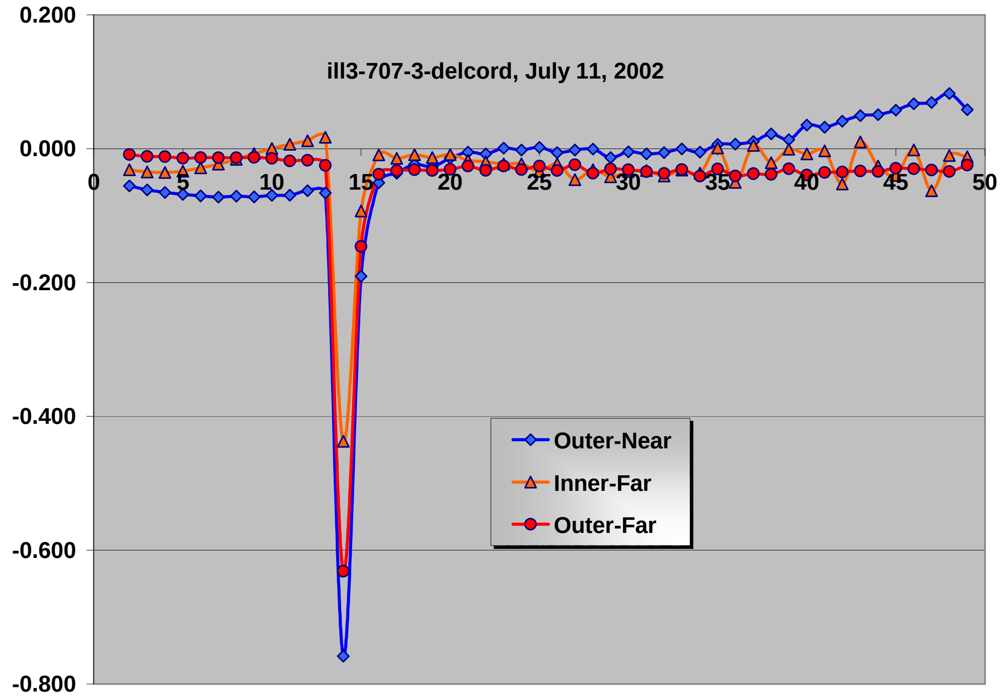

Figure 32: Delcord output for ill3-707-3.

Delcord Conclusions

Acceptable values of Delta L/L are in the range of: plus or minus .30. Sharp spikes can be view as the top edge of the cable is being in tension and the bottom edge of the cable in compression.

Program 'Part.exe', the coil end parts.

"Part.exe' creates a 50 point data file of each surface edge of an end part. The program uses the files created with program 'Bend'. To be clear about the names of the files, the .ins and .out remember that program 'Bend' is creating files, which represent cable groups. Program 'Part' is creating files that represent that area between, inside and outside the cable group. For example: the inside layer lead end 'spacer1' uses files from cable groups 2 and 3. Cable group 2 has .ins and .ous files. The .ins file is used to create the outside surface of the key and the .ous file is used to create the inside surface of the spacer1 end part. The .ins file of group 3 is used to create the outside surface of the spacer1. Therefore the .ins file of the cable is used to create the outside surface of the part and the .ous file of the cable is used to create the inside surface of the part.

PROGRAM PART
============

Program 'Part.exe' example run.

```
 Please provide specifications of the desired coil end part

 DESIRED UNITS:
  Enter 1 for INCHES
  Enter 2 for MILLIMETERS
2

 COIL SPECIFICATION:
  Enter 1 for INNER coil
  Enter 2 for OUTER coil
1

 END SPECIFICATION:
  Enter 1 for LEAD end
  Enter 2 for RETURN end
1

 PART SPECIFICATION:
  Enter 1 for KEY
  Enter 2 for SADDLE
  Enter 3 for SPACER
  Enter 4 for FILLER
  Enter 5 for SHELF
3

 Please enter the INNER COIL winding direction of
 the magnet this part has been designed for :
  Enter  1 for CLOCKWISE inner coil
  Enter -1 for COUNTER-CLOCKWISE inner coil
1

 If the part behind this spacer has a shelf attached to
 it, this spacer will require an undercut to clear the
 shelf extension. Please enter the undercut specification :
  Enter 1 for YES undercut required
  Enter 2 for  NO undercut required
2

 ASSEMBLE AN INNER COIL LEAD END SPACER
 ======================================
```

Please enter the file name dot type of the
file which contains the data for the positive-X
inner lateral surface of the SPA :
ill1.ous

Please enter the Z-axis origin difference that
applies to this surface of the SPA, in millimeters :
0

Please enter the file name dot type of the
file which contains the data for the positive-X
outer lateral surface of the SPA :
ill2.ins

Please enter the Z-axis origin difference that
applies to this surface of the SPA, in millimeters :
5

Please enter the file name dot type of the
file which contains the data for the negative-X
inner lateral surface of the SPA :
ilr1.ous

Please enter the Z-axis origin difference that
applies to this surface of the SPA, in millimeters :
0

Please enter the file name dot type of the
file which contains the data for the negative-X
outer lateral surface of the SPA :
ilr2.ins

Please enter the Z-axis origin difference that
applies to this surface of the SPA, in millimeters :
5

Please exit program and check the files entered for this part.
The Z-coordinates of point 100 and point 300 do not match.

A new file will be created to contain the formatted
output of this program. Please enter the desired name
of this new file (no file type or separating period) :
ilspacer1

Please enter todays date (example: 07-MAR-90) :
13-Jan-03

DESIRED OUTPUT FORMAT :
Enter 1 for fifty-points-per-curve ANVIL format and IDEAS.
Enter 2 for twenty-points-per-curve IDEAS format
Enter 3 for twenty-points-per-curve PART DATA SHEET
Enter 4 to quit and exit program
1

New file completed

Do you wish to create another new file with
a different format to represent this part?
DESIRED OUTPUT FORMAT :
Enter 1 for fifty-points-per-curve ANVIL format
Enter 2 for twenty-points-per-curve IDEAS format
Enter 3 for twenty-points-per-curve PART DATA SHEET
Enter 4 to quit and exit program
4

EXITING PROGRAM PART

The .50p files, created with program 'Part', will be used with I-deas for solid model part creation. Anvil will be used for surface inspection data files and also for the creation of additional files with the extensions of .gen, .igs and .dxf.

Create a .50p file for each End part of our magnet. Move them from Unix to your P.C.. Create a sub-directory named '50pfiles' and save them in there.

I-deas: SMEPP program, solid model part creation.

1.) Start I-deas.
2.) Create a new model file.
3.) Set units to millimeters.
4.) File.
5.) Program files.
6.) Run.
7.) Select SMEPPv3.prg, located at D:\ms_scratch\SMEPP.
8.) Open
9.) OK
10.) Is workbench empty?
11.) Yes
12.) Millimeters, units.
13.) Specify volume closure tolerance in millimeters (0.07).

14.) Sometimes when a part does not come out correctly with the default value (0.07), then using values from 0.25 to 0.5 helps in creating the solid model. Record the value you use.
15.) Select part type to build.
16.) LSP-Lead End Spacer.
17.) DON-Done with entering data.
18.) Enter Lead End Spacer data file name.
19.) D:\irq70\ilspacer1.50p
20.) Enter the part name
21.) ilspacer1x
22.) Enter correct origin shift (5).
23.) 5
24.) Enter correct origin shift (5).
25.) 5
26.) The program will now build the part. This can take as long a 45 minutes. Now watch for the following.
27.) Do you want to use tolerance checking? Looking at the points, displayed on the screen, if the edges converge to a sharp edge then tolerance checking should be selected. The other end should have a wide edge and tolerance checking is not necessary.
28.) Yes- yes edges are close.
29.) No- Edges are fine.
30.) Wait for your part.
31.) Check the part to be sure it is a closed solid model. Do this by assigning a material to it and check its properties. It should give a closed volume value.
32.) Save the part in a library.
33.) Save the model as an iges file.

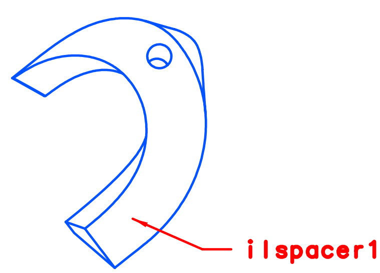

Figure 33: ilspacer1

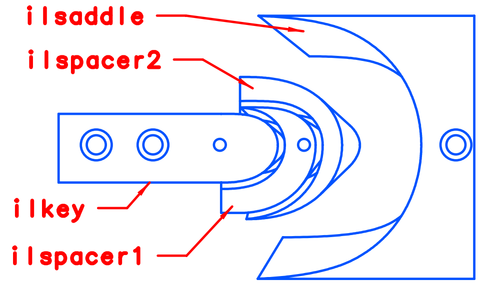

Figure 34: Inner layer, Lead end parts.

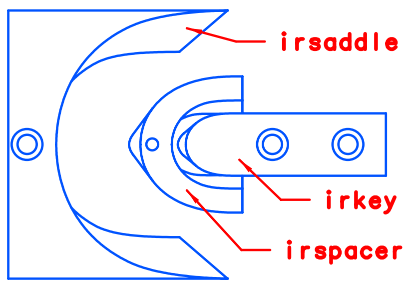

Figure 35: Inner layer, Return end parts.

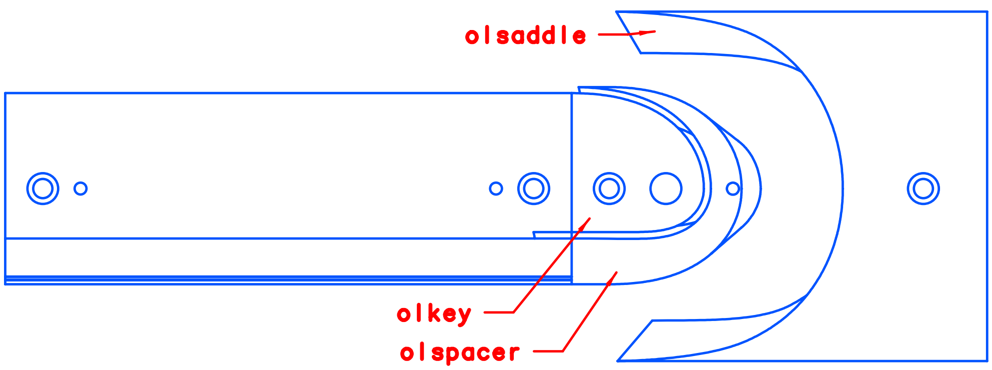

Figure 36: Outer layer, Lead end parts.

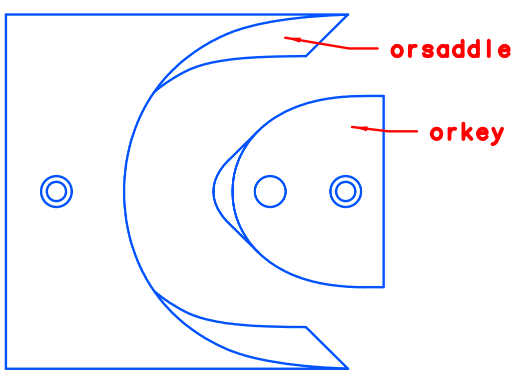

Figure 37: Outer layer, Return end parts.

The Anvil program creates files, .gen and iges used for inspection.

Anvil object

1.) Open a Unix window starting on TDSU 28.
2.) Type in ‘**ANVIL5K’**
3.) Start a new part.
4.) Use the **R**ight **M**ouse **B**utton, to go back a command.
5.) Units are millimeters. **3.**
6.) Use the **M**iddle **M**ouse **B**utton, to pick.
7.) USER
8.) CUS .2
9.) READ PNTS
10.) Select the type of part to make.
11.) SPACER
12.) The .50p files must be in a Unix directory.
13.) Enter the file name, followed by two (2) carriage returns.
14.) Select File
15.) As GEN
16.) Select the Green File Icon.
17.) Export
18.) DXF
19.) Enter the file name.
20.) Standard Log file
21.) Entire Part
22.) Version 11 or greater

Anvil export file

1.) ANVIL 5K
2.) EXPORT
3.) IGES
4.) Enter the Iges file name.
5.) LOG FILE
6.) STANDART ENTIRE PART
7.) SETUP FILES NAME [SYSTEM DEFAULT]
8.) OUTPUT CONTROL
9.) **RMB**
10.) **RMB**
11.) **RMB**
12.) **RMB**
13.) Read in the Iges file into I-deas to check the rulings.

Conclusion

Keep a well-organized folder and save the files with a consistent and meaningful naming convention.

APPENDIX

Minimum Number of End Parts Required:

Let N **be the number of conductor groups in a given layer of a magnet cross-section. Then, the minimum number of end parts required for the Return End (RE) is *N + 1*, and the minimum number of end parts required for the Lead End (LE) is *2 * N*. This implies, that the total number of end parts required for a given layer is at least *3 * N + 1*. It should be noted that a larger number of end parts would be required if any given conductor group is split into two or more conductor groups at the end.**

References

[1] S. Yadav, "Effect of BEND Parameters-Shift and Blunt On the Design of Super conducting Magnet End Parts," Fermilab Technical Note TD-01-058, (2001).

[2] J.S. Brandt, A. Simmons, "Coil End Part Design Procedure" Fermilab Technical Note TD-98-053, (1998).

[3] S.Yadav, "On the Optimal Choice for the Bend Parameter A-Length for the Design of Super conducting Magnet End Parts. Fermilab Technical Note" TD-01-059, (2001).

[1[1]] HFM Quadrupole Model-Inner Layer-Coil Assembly, 5520-MC-411370.

Flow chart for design procedure